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Human capital is the key to the IT productivity paradox[*]

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Abstract

Unlike previous analyses, we consider (i) possible externalities in the use of IT and ii) IT and human capital interactions. Examining, hypothetically, the statistical consequences of erroneously disregarding (i) and (ii) we shed light on the small or negative growth effects found in early studies of the effects of IT on productivity growth, as well as the positive impacts reported more recently. Our empirical analysis uses a 14-industry panel for Swedish manufacturing 1986-95. We find that human capital developments made the average effect of IT essentially zero in 1986 and steadily increasing thereafter, and, also, generated large differences in growth effects across industries.

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1 Introduction

The IT productivity paradox was formulated in response to the fact that the massive investments in information technology (IT) that started around 1980 did not seem to have any positive effects on productivity growth. In the words of Nobel laureate Robert Solow: ”You can see the computer age everywhere but in the productivity statistics.” [Solow (1987)]

In recent years, the original focus on computers has been broadened to include also communication devices: the concept of IT has been extended to ICT, information and communication technology. In this paper, we account for the development of communications equipment. We have kept the term IT, however.

In empirical studies, the IT productivity paradox has been verified in analyses based on early (pre–1990) data for the U.S. and Canada. Mostly, the results show either very small or insignificant effects of IT on productivity growth; see for instance Harris & Katz (1991) and Parsons, Gotlieb, & Denny (1993). Indeed, some studies have reported significantly negative effects; cf. Loveman (1988) and Berndt & Morrison (1995). Some of the explanations suggested for these counter-intuitive results are: the time required for IT investments to yield productivity increases has been underestimated, the magnitude of the investments have been overestimated and measurement problems on both the input side and the output side have concealed the productivity effects.

However, a couple of more recent studies, using data extending to the end of the 1990’s, have found productivity–increasing effects of IT. Oliner & Sichel (2000) argue that the reason why there were no effects earlier is that, in the U.S., IT investments did not really take off until 1995. When they did, the effects were substantial, however: Oliner & Sichel claim that

IT accounted for about two–thirds of the acceleration in the labor productivity between the first and second halves of the 1990's.
Bresnahan, Brynjolfsson, & Hitt (2002), while focusing primarily on skill-biased technical change rather than productivity, make an important contribution towards the resolution of the IT productivity paradox by extending the idea of capital-skill complementarity hypothesis discussed by Griliches (1969) and Lucas (1990). Bresnahan et al. (op.cit.) argue that too much attention has been paid to IT investments and too little attention has been paid to work organization and human capital structure. Accounting for both IT and human capital, they find that the balance between the two is crucial. Firms with high levels of both IT and human capital are found to be the most productive. More interesting: firms with low levels of *both* IT and human capital are shown to be more productive than firms that are high on IT and low on human capital, or vice versa.

The framework we suggest in this paper is similar to the Bresnahan et al. (op.cit.) approach in the sense that we, too, conjecture that human capital is a key element in the explanation of the IT productivity paradox. However, we extend the analysis by incorporating a phenomenon often discussed in the context of endogenous growth theory, namely knowledge spillovers. While it seems very natural to consider knowledge spillovers in an evaluation of the productivity effects of IT, these have barely been discussed in earlier studies.

The next section contains a review of some attempts to explain the IT productivity paradox. In Section 3 we develop a simple stylized growth model. By means of this model we discriminate between some of the suggested explanations for the IT productivity and, second, propose a way to account for knowledge spillovers.

Our empirical analysis is based on data for 14 industries in the Swedish manufacturing sector observed annually during the period 1986–95. It appears that in the Swedish manufacturing sector the productivity-enhancing effects of IT started to show already in the first half of the 1990s, i.e. a couple of years earlier than, e.g., in the U.S. Otherwise, the developments in Sweden seems to have been qualitatively similar to that in several other countries. Our data are described in Section 4 and the results are provided in Section 5. Section 6 contains a summary of our results and our conclusions.

2 Literature review: attempts to explain the paradox

For brevity, we here only provide a very condensed and selective list of some the explanations suggested for the IT productivity paradox.[1]

1. *Investments in IT became massive only towards the end of the 1990s.* Thus, early analyses were unable to capture positive growth effects from IT simply because, at the time, these investments were still comparatively small. Studies using later data should be able to discern positive growth effects. This view is supported by the study by Oliner & Sichel (2000). However, this explanation says nothing about the significant negative effects of IT on productivity estimated by, e.g., Loveman (1988) and Berndt & Morrison (1995).
2. *It takes time before the productivity-enhancing effects of a new technology can be realized.* This point has perhaps been most convinc-

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[1] For a more extensive discussion see, e.g., Triplett (1999). Also, for the view that there is essentially no paradox to explain, because the importance of the introduction of IT has been vastly exaggerated, compared to the significance of other technological developments like the adoption of electricity, see Gordon (2000).

ingly made by David (1990). From an empirical point of view, this explanation is similar to the previous one. An important difference, however, is that this explanation can account for (initial) negative effects of IT on productivity, provided that the diffusion of IT use is associated with learning costs that decrease over time, as a function of the increasing number of users.

This explanation also points to the importance of (positive) externalities. More wide-spread knowledge about (how to exploit) IT will speed up the rate of diffusion. The resulting increase in people with access to IT will raise the benefits accruing to individual users, which will further accelerate diffusion. The importance of this spiralling effect has been especially notable in the 1990's, with the rapidly expanding use of email and the Internet.

3. *No account has been taken of the complementarity between IT and skilled workers.* Although the capital-skill complementarity hypothesis was put forward already by Griliches (1969), the connection between IT and human capital has almost invariably been disregarded in assessments of the productivity effects of IT.[2] Presumably, this is primarily due to lack of data. However, by matching two different data sets Bresnahan, Brynjolfsson, & Hitt (2002) have overcome this problem. Splitting their data into four categories according to whether firms are "high" or "low" on IT and human capital, they find high levels of productivity in firms that are either high on both IT and human capital *or* low in both of these dimensions. Relatively lower levels of productivity are found in firms that are high in one

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[2] However, complementarity between IT and skilled workers has been documented in several studies of labor demand and skill-biased technical change. Two seminal contributions are Berman, Bound, & Griliches (1994) and Autor, Katz, & Kreuger (1998). For a study using Swedish data, see Mellander (1999).

of the two dimensions and low in the other.[3] Using a different approach, Kaiser (2003) also finds strong evidence for complementarity between expenditures on IT capital and outlays for IT personnel.

4. *IT is a general purpose technology (GPT), the efficient implementation of which requires changes in work practices and skill upgrading.* This explanation contains elements of explanations 2 and 3. The idea is that the introduction of GPTs like IT will initially lead to a slowdown in productivity, as it takes time to implement and learn to use the GPT efficiently. In particular, assuming skilled labor to have a learning advantage over unskilled labor, the theory holds that skill premia will rise, inducing an increased supply of skills. When the increased supply comes about and the work organization is properly adapted to the GPT, productivity starts increasing again. The notion of GPTs was introduced by Bresnahan & Trajtenberg (1995) and the relation between GPTs and productivity growth is discussed in, e.g., Helpman & Trajtenberg (1998), and Greenwood & Yorukoglu (1997).

5. *Mismeasurement of outputs.* According to this explanation, the use of information technology has increased the quality of existing products and services and created new goods, neither of which are (fully) captured in the official statistics. This has led to a downward bias in the estimated growth effects; see, e.g., Brynjolfsson (1993) and Dean (1999). Nevertheless, it is essential to point out, like Lee & Barua (1999) do, that efficiency related gains in the production of

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[3] A related approach is taken by Siegel (1997), who considers the possibility that the investments in IT may induce enhanced efficiency of labor which, in turn, positively affects productivity growth. He finds some, although not unambiguous, support for this hypothesis.

the "old" goods should still be accounted for by conventional output measures. That is to say, while mismeasurement of output certainly is part of the puzzle it cannot resolve it entirely.

6. *Mismeasurement of inputs.* On the input side the issue of mismeasurement is less clear-cut than on the output side. On the one hand, it can be argued that early (U.S.) measures of IT were overstated because they included equipment that one would not ordinarily associate with IT like, e.g., typewriters and accounting machinery.[4] On the other hand, the often noted difficulties to adjust for quality increases in IT price indexes implies a tendency to underestimate the volumes of IT investments.[5] And the presence of positive externalities in the use of IT, cf. the second point above, points in the same direction. Failure to account for these externalities will, again, bias measures of IT inputs downwards.
7. *Overinvestments in IT, in the latter half of the 1980s.* This explanation has been suggested by Morrison (1997), based on the finding that in U.S. manufacturing industries estimated benefit–cost ratios (Tobin's q) for IT capital dropped significantly below 1 by the mid 1980's. It is natural to interpret the term "overinvestment" in a relative sense here, i.e. that IT investments were too large compared

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[4] These were included in Bureau of Economic Analysis category "Office Computing and Accounting Machinery; cf Berndt & Morrison (1995). After 1982 this category was replaced by "Information Processing and Related Equipment", see Lee & Barua (1999).

[5] For a hedonic approach to the estimation of price indexes for computers, see Berndt, Griliches & Rappaport (1995) and Berndt & Rappaport (2001).

Observing that IT involves non–computer equipment, too, Lee & Barua (1999) have turned upside down the argument about how quality adjustment affects the measured volumes of IT. In their examination of the study by Loveman (1988), they argue that by applying a computer price index to all types of IT Loveman *overestimated* the volumes of IT investments, as computer prices have fallen faster than the prices of other IT products. While this criticism is probably foremost valid with respect to early definitions of IT that involved many items whose IT character could be questioned, the argument is supported by Jorgenson's (2001) study of relative prices for different kinds of IT equipment in the US since the late 1940s.

to outlays on other factors of production, notably human capital; cf. points 3 and 4.

There are thus rather diverse results on the connection between IT and growth, and the explanations for these findings are quite diverse, too.

3 A stylized model

We here consider a stylized version of the model that we use in our empirical analysis. Our discussion serves two purposes. The first is to reconcile the different results of the earlier studies and to discriminate between some of the explanations that have been suggested for the IT productivity paradox. The second purpose is to consider how knowledge spillovers and capital-skill complementarity might affect productivity growth.

Our stylized model captures four features: i) measurement error in the IT input variable(s), ii) mismeasurement of output, iii) positive externalities in the use of IT, and iv) the connection between IT and human capital.

The analysis is consistent with both a neoclassical growth theory framework and with endogenous growth models. We can thus here disregard the fact that these two theoretical frameworks have different implications for the empirical analysis, notably with respect to how IT and human capital are operationalized.[6]

Regarding feature i., it was noted in Section 2 that the IT measurement error can be both negative and positive. A simple specification allowing for this is

$$IT_t^* = IT_t + w_t \tag{1}$$

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[6] The empirical specification of the model will be discussed in Section 4.2.

where IT_t^* is the observed mesure of IT in period t, IT_t the true measure and w_t a random error, such that

$$E\left(w_t\right) = 0, \quad Var\left(w_t\right) = \sigma_w^2, \quad Cov\left(IT_t, w_t\right) = 0. \tag{2}$$

With respect to feature ii., non-recorded quality improvements in output should introduce a downward bias in measures of productivity growth (cf. point 5 in Section 2). Like the mismeasurement of IT, the mismeasurement of output is likely to vary over time, cf. Basu et al. (2003). We therefore specify the difference between the firm's true rate of TFP growth, g_t, and the observed rate, g_t^*, as a random variable with positive expectation, β_0, according to

$$g_t - g_t^* = \beta_0 + u_t\,, \qquad \beta_0 > 0, \tag{3}$$

and

$$E\left(u_t\right) = 0, \quad E\left(u_t^2\right) = \sigma_u^2\,, \quad Cov\left(u_t, w_t\right) = 0. \tag{4}$$

Feature iii. can be modeled by assuming that the productivity effects from IT at the firm and industry level are affected by the use of IT in the aggregate economy; see the last paragraph of point 2, Section 2. Assuming that there is an index of the Total Use of IT in the Swedish Economy, $TUITE$, we posit that $TUITE$ has the effect of scaling up the IT input. Using an increasing function, ψ, and allowing for a delayed impact on the rate of growth we arrive at the following

$$\text{direct effect of } IT \text{ on } g_t: \quad \beta_{1t} \cdot IT_{t-1}\,; \quad \beta_{1t} = \psi\left(TUITE_{t-1}\right) \text{ and } \psi' > 0. \tag{5}$$

The scaling effect can thus be expressed in terms of a time-varying parameter, β_{1t}. Note that we do *not* assume that this parameter is positive, *a priori*.

The motivation for (5) is that, by definition, an externality is an effect which is not accounted for by individual firms and, hence, shows up in TFP growth. In a neoclassical context, this would mean that the capital rental price of IT would overstate the real cost of IT capital.[7] In an endogenous growth context, as in, e.g., Barrro and Sala–i–Martin (1999) it is natural to relate to a learning–by–investing mechanism; as successively more firms invest in IT, the knowledge about the properties of the new technology increases and becomes more widespread.

With respect to feature iv., our analysis will be based on the maintained hypothesis that information technology and human capital are complements, in accordance with, e.g., Bresnahan et al. (2002) and Kaiser (2003). We model the complementarity by means of an interaction variable, taken to affect g_t positively. Allowing, again, for a delayed impact we get an

$$\text{indirect effect of } IT \text{ on } g_t : \quad \beta_2 \cdot (IT \times HC)_{t-1} \; ; \quad \beta_2 > 0. \qquad (6)$$

Ordinarily, interaction effects should be captured already in the measure of productivity growth.[8] In the context of externalities in the use of IT and/or measurement error in the IT input, the interaction effect may not be properly accounted for, however. There may be knowledge spillovers arising through networks: employees working with computers form networks (via the Internet) with colleagues in other firms, networks which facilitate the transfer of knowledge.[9]

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[7] Siegel (1997) tries to capture IT externalities within a neoclassical framework. However, instead of considering the total use of IT in the economy he uses a measure of the IT investments made by the industry's suppliers.

[8] We are assuming here that the TFP growth measure corresponds to a flexible representation of the technology, implying that it allows for interactions between inputs; see Section 4.1

[9] One might wonder why we allow for both first- and second-order effects of IT on productivity growth but only for a second-order effect of HC. The reason is that the

Taking the total effect of IT on g_t to be the sum of the direct effect (5) and the indirect effect (6) and using (3) we obtain the following equation:

$$g_t^* = -\beta_o + \beta_{1t} IT_{t-1} + \beta_2 \left(IT \times HC\right)_{t-1} - u_t\,. \tag{7}$$

By (7), the effect of "true" IT on the observed rate of TFP growth equals

$$\frac{\partial g_t^*}{\partial IT_{t-1}} = \beta_{1t} + \beta_2 HC_{t-1}\,. \tag{8}$$

Note that although the effect of IT on productivity growth is increasing in human capital, the total effect can be negative, provided that β_{1t} is negative and sufficiently large in magnitude.

Before proceeding to analyse the implications of our simple model, a word of caution is in order. A causal interpretation, from IT and HC to g_t^*, is justified only if the one year lag on IT and HC makes it possible to treat these variables as predetermined. This, in turn, hinges upon the absence of serial correlation in the data. This is an empirical matter that we consider in Section 5.2

Using the framework given by equations (1) – (8) we now discuss three issues that have arisen in connection with earlier studies:

I. Can the negative effects of IT on productivity growth found in studies based on pre–1990 data be explained by measurement error in the IT variable as argued by Lee & Barua (1999), or are the results indicative of a truly negative return to early IT investments, as argued by Morrison (1997)?

II. Why is it that models similar to the one just outlined yield positive returns when applied to later data?

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features i – iv above, do not involve mismeasurement in human capital and also not externalities in human capital *per se*. The externalities that we consider are associated with IT, either through IT investments or through the use of IT. However, from an *empirical* point of view there might nevertheless be a place for a first-order effect of HC in the model. This point is discussed in Section 5.2.

III. If complementarity between IT and skilled labor is allowed for, like in Bresnahan et al. (2002), what will happen to the estimated direct effect?

Assume, first, that g_t^* is simply regressed on IT_{t-1}^*, using data for the pre–1990 period and post–1990 period, respectively. This implies that the measurement error in IT is ignored, that the variable $(IT \times HC)_{t-1}$ is omitted, and that no account is taken of the fact that β_{1t} is a time–varying coefficient. For illustrative purposes we will here assume that the function ψ is a step function, taking on the values $\overline{\beta}_{1,\text{pre-90}}$ during the pre-1990 period $\overline{\beta}_{1,\text{post-90}}$ in the post-1990 period.

To derive the probability limit of the OLS estimate of β_{1t} under this conditions, we apply a result stated in Lam & Schoeni (1993).[10] This yields

$$\text{plim}\left(\widehat{\overline{\beta}}_{1,\text{K}}\right) = \overline{\beta}_{1,\text{K}} - \overline{\beta}_{1,\text{K}} \cdot \lambda + \beta_2 \widehat{\theta}\,(1-\lambda)\,, \qquad \text{K} = \text{pre-90, post-90} \tag{9}$$

where the IT measurement error is accounted for by the parameter λ, defined as

$$\lambda \equiv \frac{Var\,(w)}{Var\,(IT^*)}\,, \tag{10}$$

and $\widehat{\theta}$ is the coefficient from a hypothetical regression of $IT \times HC$ on IT:

$$\widehat{\theta} = \frac{Cov\,(IT \times HC, IT)}{Var\,(IT)}\,, \qquad \widehat{\theta} > 0. \tag{11}$$

From (9) it can be seen that the bias in the estimate of $\overline{\beta}_{1,\text{K}}$ has two components. The first, $-\overline{\beta}_{1,\text{K}} \cdot \lambda$, is the measurement error bias (MEB). The second component, due to omission of the variable $IT \times HC$, is the omitted variable bias (OVB). While the OVB is invariably positive, given

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[10] In a returns to schooling context, Lam & Schoeni (op.cit.) consider how the estimated effect on earnings from another year of schooling is affected when data on "ability" are lacking and there is measurement error in the schooling variable.

the assumptions $\beta_2 > 0$ and $\widehat{\theta} > 0$, the sign of the MEB is determined by the sign of the true parameter $\overline{\beta}_{1,\mathrm{K}}$. If $\overline{\beta}_{1,\mathrm{K}}$ is positive the MEB will be negative, and if $\overline{\beta}_{1,\mathrm{K}}$ is negative, the MEB will be positive.

Equation (9) can be used to derive bounds on the probability limit of the OLS estimate $\widehat{\overline{\beta}}_{1,\mathrm{K}}$. These bounds are given in Table 1, for various assumptions about the true parameter and the magnitude of the omitted variable bias.

We can now consider issue I. As can be seen in Table 1, the estimated effect of IT on productivity growth can be negative *only* if the corresponding true effect is negative. In this case, c), the true effect is negative *and* smaller than the lower bound of $\operatorname{plim}\left(\widehat{\overline{\beta}}_{1,\text{pre-90}}\right)$; this is so because the omitted variable bias, $\beta_2\widehat{\theta}$, is positive. Furthermore, this conclusion is unaffected by measurement error in the IT variable. The upper bound of $\operatorname{plim}\left(\widehat{\overline{\beta}}_{1,\text{pre-90}}\right)$ is equal to zero, irrespective of whether there is measurement error or not. Our analysis thus supports Morrison's (1997) suggestion of overinvestment in IT during the latter part of the 1980's, as overinvestment would, eventually, result in a negative effect of IT on productivity. And, as our conclusion is invariant to measurement error in the IT variable, we reject the claim in Lee & Barua (1999) that measurement errors were behind estimated negative effects of IT on productivity growth.[11]

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[11] Actually, Lee & Barua state that ”.... the negative contribution of IT .... is attributable primarily to the choices of the IT deflator and modeling technique.” However, they do not provide any assessment making it possible to disentangle the impacts of these two factors.

Table 1:_ Ranges for the probability limit of the OLS estimator of $\overline{\beta}_{1,\mathrm{K}}$,for different signs of the true effect and different magnitudes of the omitted variable bias

a)	$\overline{\beta}_{1,\mathrm{K}}>0$	$\Longrightarrow$	$0\leq\mathrm{plim}\left(\widehat{\overline{\beta}}_{1,\mathrm{K}}\right) \leq \overline{\beta}_{1,\mathrm{K}}+\beta_2\widehat{\theta}$
b)	$\overline{\beta}_{1,\mathrm{K}}<0$ and $\beta_2\widehat{\theta}>\left\|\overline{\beta}_{1,\mathrm{K}}\right\|$	$\Longrightarrow$	$0\leq\mathrm{plim}\left(\widehat{\overline{\beta}}_{1,\mathrm{K}}\right) \leq \overline{\beta}_{1,\mathrm{K}}+\beta_2\widehat{\theta}$
c)	$\overline{\beta}_{1,\mathrm{K}}<0$ and $\beta_2\widehat{\theta} < \left\|\overline{\beta}_{1,\mathrm{K}}\right\|$	$\Longrightarrow$	$\overline{\beta}_{1,\mathrm{K}}+\beta_2\widehat{\theta} \leq\mathrm{plim}\left(\widehat{\overline{\beta}}_{1,\mathrm{K}}\right) \leq 0$

Note: The index K denotes either pre-90 or post-90

We next consider point II., i.e. why analyses on more recent data find positive effects of IT on productivity growth, thus reversing the results of earlier studies. The surge in IT investments, coupled with falling computer prices, meant that IT became available to a rapidly increasing number of people. That, in turn, increased the positive externalities associated with the use of IT, cf. equation (5). As mentioned above, we will for simplicity model this by specifying:

$$\beta_{1t} = \begin{cases} \overline{\beta}_{1,\text{pre-90}} & \text{for} \quad t \leq 1990 \\ \overline{\beta}_{1,\text{post-90}} & \text{for} \quad t > 1990 \end{cases} \qquad \overline{\beta}_{1,\text{post-90}} > \overline{\beta}_{1,\text{pre-90}} \tag{12}$$

It should be noted that (12) is not sufficient to determine the sign of $\overline{\beta}_{1,\text{post-90}}$. If $\overline{\beta}_{1,\text{pre-90}} < 0$ then $\overline{\beta}_{1,\text{post-90}}$ may be negative, too. Unfortunately, the sign of the estimate $\widehat{\overline{\beta}}_{1,\text{post-90}}$ is no help here. In Table 1, we see that $\mathrm{plim}\left(\widehat{\overline{\beta}}_{1,\text{post-90}}\right) > 0$ is consistent with both $\overline{\beta}_{1,\text{post-90}} > 0$ and $\overline{\beta}_{1,\text{post-90}} < 0$; cf cases a) and b), respectively. However, we can discriminate between the two cases by expanding the simple OLS regression to include a vector of proxy variables for the omitted variable, i.e. $IT \times HC$. This will affect the estimate of $\overline{\beta}_{1,\text{post-90}}$ differently depending on the sign of the true parameter $\overline{\beta}_{1,\text{post-90}}$. To show this, denote vector of proxy variables by $\mathbf{P}$, and the corresponding estimate of $\overline{\beta}_{1,\mathrm{K}}$ by $\widehat{\overline{\beta}}_{(1,\mathrm{K})\cdot\mathbf{P}}$. Then

$$\begin{aligned}\operatorname{plim}\left(\widehat{\overline{\beta}}_{(1,\mathrm{K})\cdot\mathbf{P}}\right) &= \overline{\beta}_{1,\mathrm{K}} - \overline{\beta}_{1,\mathrm{K}}\tfrac{\lambda}{1-R^2_{IT^*\times HC,\mathbf{P}}} \\ &\quad + \beta_2\widehat{\theta}\,(1-\lambda)\cdot\phi\,(IT^*, IT^*\times HC, \mathbf{P})\end{aligned} \tag{13}$$

where $R^2_{IT^*\times HC,\mathbf{P}}$ denotes the R^2 obtained when $IT^* \times HC$ is regressed on $\mathbf{P}$, and $\phi\,(\cdot)$ is a function that under fairly general conditions satisfies $0 < \phi\,(\cdot) < 1$.[12]

Comparing (9) and (13) we note that

$$\overline{\beta}_{1,\mathrm{K}} > 0 \Longrightarrow \operatorname{plim}\left(\widehat{\overline{\beta}}_{(1,\mathrm{K})\cdot\mathbf{P}}\right) < \operatorname{plim}\left(\widehat{\overline{\beta}}_{1,\mathrm{K}}\right). \tag{14}$$

The implication (14) is due to the fact that the inclusion of proxy variables affects the measurement error bias (MEB) and the omitted variable bias (OVB) in the same direction when $\overline{\beta}_{1,\mathrm{K}} > 0$. With respect to the MEB, the fact that $\left(1 - R^2_{IT^*\times HC,\mathbf{P}}\right) \in]0,1[$ implies that including proxies makes the MEB larger in magnitude, i.e. smaller because of the minus sign. The OVB, while positive, becomes smaller, too, because $0 < \phi\,(\cdot) < 1$.

On the other hand, if $\overline{\beta}_{1,\mathrm{K}} < 0$ the effect of the proxy variables is ambiguous, the ambiguity being due to the fact that in this case the MEB and the OVB change in different directions.

Thus, by studying the effects of including proxy variables we should be able to infer the sign of the true parameter $\overline{\beta}_{1,\text{post-90}}$. If $\overline{\beta}_{1,\text{post-90}}$ is indeed positive, then the estimate of $\overline{\beta}_{1,\text{post-90}}$ should be positive when human capital variables are excluded from the regression and this positive estimate should decrease towards zero when proxy variables for human capital are included.

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[12] Like (9), this equation draws on Lam & Schoeni (1993). They provide a similar expression to assess the effect on the estimated return to schooling when a proxy variable for the missing ability measure is included in the regression.

The analysis also provides the answer to issue III. It shows that the answer depends on the sign of the true direct effect. If the true direct effect is positive, allowing for indirect effects will decrease the estimated direct effect, cf.(14). If, on the other hand, the true direct effect is negative, allowing for indirect effects will have an ambiguous impact on the estimated direct effect.

4 Data and empirical specification

Our empirical analysis covers 14 industries in the Swedish manufacturing sector, observed annually over the period 1986–95. The industry codes are given in Table 2. To indicate the relative size of the industries we also show their shares in manufacturing employment in the middle of the observation period. The data are from the official statistics produced by Statistics Sweden; from the National Accounts, the Employment Register, the Labor Force Surveys, var-

Table 2: The industries considered and their shares in total manufacturing employment in 1991.

Industry code	Industry	Employment share 1991, %
3100	Food, Beverages and Tobacco	9.4
3200	Textile, Apparel & Leather	3.0
3300	Saw Mills and Wood Products	8.5
3400	Pulp, Paper and Printing & Publishing	14.7
3500	Chemical, Plastic Products. and Petroleum	7.9
3600	Non-Metallic Mineral Products	3.3
3700	Basic Metals	4.0
3810	Metal Products	11.5
3820	Machinery & Equipment, not elsewhere classified	13.5
3830	Electrical Machinery, not elswhere classified	8.1
3840	Transport Equipment, except Shipyards	12.3
3850	Instruments, Photographic & Optical Devices	2.2
3860	Shipyards	0.8
3900	Other Manufacturing	0.8
3000	Total Manufacturing	100.0

Note: The classification system used here is very close to the ISIC codes.

ious Investment Surveys and the Trade Statistics.

The cross-sectional dimension of the data set has been determined by the most detailed break–down of IT investments provided in the Investment Surveys. In the time series dimension, the starting point is given by the first year of the Employment Register. The end point is the result of a change in the industrial classification system, making it impossible to extend the time series beyond 1995.

4.1 The growth rate in total factor productivity

The yearly TFP growth rates have been computed by means of a Törnqvist index. This index corresponds to the translog production function and allows for interactions among inputs like, e.g., complementarity between IT and human capital.[13]

Suppressing industry indexes and denoting the volume of gross output by Y and the volume of input i by X_i, the TFP growth rate g, is defined as

$$g_t \equiv \Delta \ln TFP_t = \Delta \ln Y_t - \Delta \ln X_t \qquad t = 1986, ..., 1995 \tag{15}$$

where Δ is the difference operator, defined such that $\Delta \ln Z_t \equiv \ln Z_t - \ln Z_{t-1}$. The growth in aggregate input, X_t, is given by:

$$\Delta \ln X_t = \sum_{i=1}^{8} \overline{w}_{i,t} \Delta \ln X_{i,t},. \tag{16}$$

where the weights $\overline{w}_{it}$ are defined in terms of average cost shares according to

$$\overline{w}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t-1}X_{i,t-1}}{\sum_{k=1}^{n} P_{k,t-1}X_{k,t-1}} + \frac{P_{i,t}X_{i,t}}{\sum_{k=1}^{n} P_{k,t}X_{k,t}}\right), \tag{17}$$

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[13] Cf. Jorgenson et al. (1973) and Caves et al (1982).

and P_i is price of input i.

We consider the following eight inputs, which will be discussed below,
K_C = Stock of computer equipment capital,
K_M = Stock of non-computer equipment capital,
K_S = Stock of structure capital,
L_1 = # of full-time employees with elementary school (less than 9 years),
L_2 = # of full-time employees with 9 year compulsory school,
L_3 = # of full-time employees with upper secondary school,
L_4 = # of full-time employees with tertiary and postgraduate education,
IG = Intermediate goods.

Figure 1 shows how the industry-weighted average of TFP growth has evolved over time. While the period 1986–90 showed low but stable growth, the growth rates during 1991–95 were much higher and also more volatile. Also, Figure 2 shows that the variation around the average is smaller in 1991–95 than in 1986–90. Thus, the higher average growth in the first half of the 1990s is not merely the result of high growth rates in some large industries.As noted in the introduction, the turning point apparently occurred quite early in Sweden. For instance, Stiroh (2002) estimates that the breakpoint in U.S. manufacturing was passed in 1993.

Figure 1: Weighted averages of TFP growth rates in Swedish manufacturing 1986-1995. Industry weights equal to employment shares

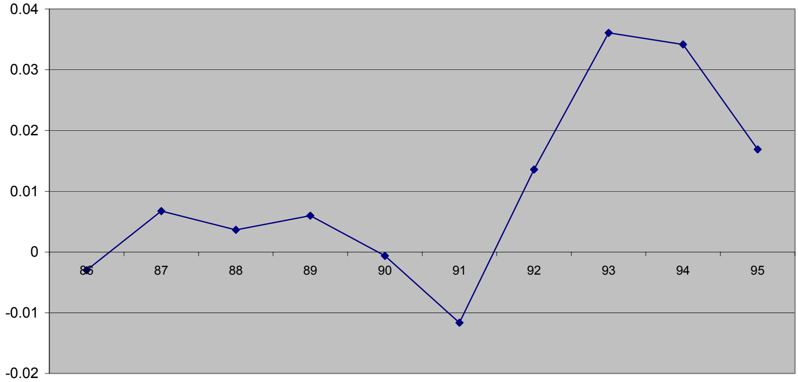
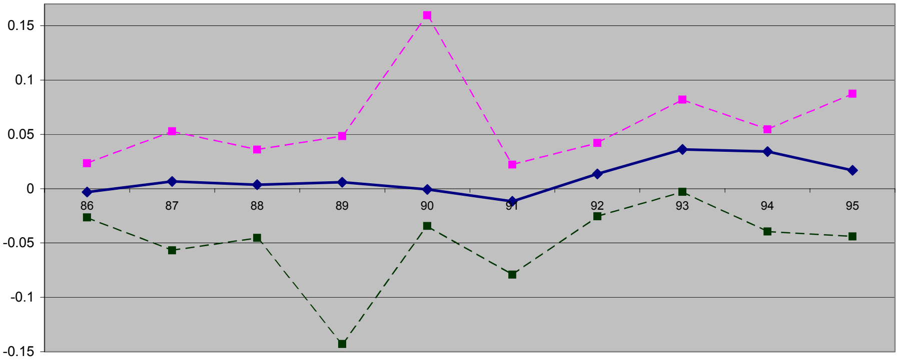


Figure 2: The industry variation around the weighted average. All observations lie within the bounds given by the dashed lines.



It can be argued, of course, that the increase in TFP growth in the latter half of the period is not only due to IT developments, but also to business cycle changes. We thus control for the business cycle in the empirical analysis, cf. Section 4.5.

4.2 Specification of the explanatory variables

We consider three alternative specifications of the explanatory variables.

The first, due to neoclassical growth theory as originally formulated by Solow (1956), implies that the explanatory variables should be specified in terms of *growth rates.* In a neoclassical context, the primary reason for explaining variations in TFP growth by means input growth rates is presence of input measurement error. While less natural, externalities can also be used as a motivation.[14]

The second framework is endogenous growth theory, which predicts that the *levels* of (some) inputs determine the rate of productivity growth. Endogenous growth theory explicitly deals with the rôle of externalities in explaining growth; see, e.g., Barro & Sala-i-Martin (1999). There are also endogenous growth models where growth is increased by devoting resources to R&D [Romer (1990) and Aghion & Howitt (1992)].Since resources devoted to R&D are essentially resources devoted to sophisticated capital equipment (IT) and highly educated workers, these models provide a motivation for the current study. Another argument can be derived from the literature on GPTs: successful implementation of a new GPT and the generation of skills needed to operate it efficiently is a cumulative process. As such, it should be better captured by the developments of stocks (of IT and human capital) than by yearly flows, i.e. growth rates.

The third framework is due to Jones' (1995, 1999) critique of endogenous growth models. Jones (1995) argues that the claim that the level of R&D should determine the rate of growth is inconsistent with empirical data. He notes, however, that a simple way to avoid that increases in the levels of inputs can increase growth without limit is to substitute input *proportions* for input levels. For instance, if resources devoted to R&D can be approximated by "research labor" then, instead of having the number

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[14] A study framed in the neoclassical tradition which considers both measurement errors and externalities is Siegel (1997).

of research workers determining the rate of growth, one could have the share of research workers in total employment.

As there are no clear theoretical arguments for preferring one of these specifications in favor of the others, we have estimated models according to each one of them. Our general conclusions can be formulated as follows. Similar to the experience of Benhabib & Spiegel (1994), the neoclassical specification with explanatory variables in growth rates yielded largely insignificant results. The level specification of the original endogenous growth models to a larger extent resulted in significant estimates but these were often implausible with respect to sign. The input proportions specification yielded the best results in terms of significance, signs and goodness-of-fit. We thus focus on this alternative.[15]

4.3 Measures of IT equipment and IT use

As our measure of IT, we use the share of computers in the total capital stock, K_C/K. The computer capital stock has been constructed by means of data on computer investments collected through investment surveys conducted by Statistics Sweden. The computer investments cover investments made both for office use and for use in the production process, e.g., CNC (computer numerically controlled) equipment and CAD / CAM – systems.[16] For the manufacturing sector as a whole, computer investments for use in the production process were 3–4 times as large as those for office use, during the period that we study.

By means of the computer investments data we have broken down

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[15] However, results corresponding to the rates and levels specifications are avaiable on request.

[16] The definition of IT investments employed here differs from definitions used in some recent U.S. studies. For example, Gordon (2000), Jorgenson & Stiroh (2000), and Oliner & Sichel (2000) define IT investments as investments in hardware, software, and telecommunications.

the industry-specific stocks of equipment capital provided in the National Accounts into computer capital stocks, K_C, and stocks of non-computer equipment, K_M. Details on the computation are provided in the Appendix.

Table 3: Capital stock shares in Swedish manufacturing

Industry	Computers			Equipment			Structures		
	1985	1990	1994	1985	1990	1994	1985	1990	1994
3100	2.8	5.5	7.8	48.6	48.8	48.7	48.6	45.7	43.5
3200	3.5	6.6	6.9	60.7	56.4	49.0	35.9	37.0	44.1
3300	3.0	17.2	12.6	47.1	33.2	39.1	49.9	49.6	48.3
3400	9.2	13.8	14.1	56.0	54.2	53.4	34.8	32.0	32.5
3500	4.0	7.0	12.1	61.4	60.4	55.5	34.6	32.6	32.4
3600	2.0	6.1	6.7	50.8	50.5	49.9	47.2	43.4	43.4
3700	2.2	9.9	10.8	56.6	50.6	51.8	41.2	39.4	37.3
3810	8.8	18.0	15.6	44.8	41.0	44.1	46.5	41.0	40.3
3820	13.4	17.8	21.0	33.5	42.0	40.5	53.1	40.1	38.5
3830	16.1	16.2	32.7	41.7	48.5	32.2	42.2	35.3	35.1
3840	19.7	21.0	36.2	30.0	36.0	25.2	50.4	43.0	38.6
3850	23.6	15.7	21.0	39.7	56.4	49.5	36.7	27.9	29.5
3860	1.9	3.1	7.2	42.3	34.9	30.2	55.8	62.0	62.5
3900	2.1	5.0	6.5	37.6	38.9	35.2	60.4	56.2	58.3
3000	7.9	13.4	17.3	49.2	47.8	44.9	42.9	38.9	37.8

Table 3 shows the shares of computers, non-computer equipment and structures in the capital stock, for the beginning, middle and end of the period.[17] In Table 3, we see that, for the manufacturing sector as a whole, the computer share in the capital stock more than doubled over the period 1985-94, from 7.9 percent to 17.3 percent. This is especially remarkable in view of the fact that computer capital depreciates much faster than other types of capital; we have assumed the rate of depreciation for computer capital to be 1/3. Table 3 also shows that in relative terms the largest increases in the computer shares took place between 1985 and 1990, rather than between 1990 and 1994. It can also be seen that there is a lot of variation across industries. This is important because the relatively short

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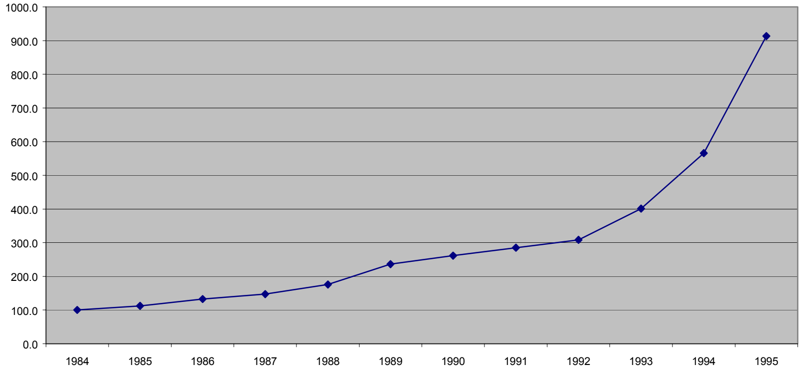
[17] The capital stocks for year t are defined as January 1.

period covered by our data makes cross-sectional variation crucial in our empirical analysis.

Figure 3: Index of total use of IT in Sweden, 1984=100



To model the externalities associated with IT, we use an index of the Total Use of IT in the Swedish Economy, $TUITE$, cf. (5). This index includes both computers & peripherals, and communication equipment. It is defined as

$$TUITE_t = PROD^N_{IT,t} + IMP^N_{IT,t} - EXP^N_{IT,t} \tag{18}$$

$PROD^N_{IT,t}$, $IMP^N_{IT,t}$, and $EXP^N_{IT,t}$ denoting volumes of production, imports and exports of IT at the national level. Figure 3 shows the evolution of $TUITE$.

It can be seen that the use of IT has increased extremely rapidly, especially from 1992 and onwards; between 1992 and 1995 the increase was threefold.

Both K_C/K and $TUITE$ are included in the regressions we with a one year lag, again to avoid endogeneity problems.

4.4 The human capital data

The human capital variables have been constructed by means of the Swedish Employment Register and the Labor Force Surveys. The Employment Register contains employee information on industry, level of education and fields-of-study, age, sex, and immigrant status, and yearly earnings. The Labor Force Surveys provide data on work hours per week, by industry and sex, enabling an approximate conversion of number of employees into full-time equivalents.[18].

Just like the use of capital, employment of labor is endogenously determined. In the empirical analysis, the human capital variables are thus also lagged one year, relative to productivity growth. Accordingly, the cross-classifications of labor for 1985, 1990 and 1994 in Table 4 are to be related to productivity growth rates in 1986, 1991 and 1995, respectively.

The four cells in the upper left corner of the three sub-tables in Table 4 are identically zero, because the cross-classification by fields-of-study is possible only for labor with at least upper secondary school. For the latter, quite detailed field-of-study information is available, however. The labels "engineering" and "business administration" are used for brevity only; both encompass several subfields.

The table shows that the human capital in the Swedish manufacturing sector changed dramatically during the period that we are studying. For instance, in 1985 almost half of the workers (49 percent) had no more than 9 years of schooling. In 1994, the share was 1/3. And, at the other end of the distribution, the share of workers with tertiary education almost doubled, from 9 to 16 percent. There is also considerable cross-section

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[18] The approximate nature of the conversion is due to the fact that the Labor Force Survey does not contain work hours by level of education.

variation; in the empirical analysis we employ cross-classifications like Table 4 that differ both by to industry and year.

Table 4: Employment shares in Swedish manufacturing, by level of education and fields–of–study, 1985, 1990 and 1994.

1985:

Level of education	Field-of-study			$\sum$
	Engineering	Business administration	”other”	
< 9 years	0	0	0.30	0.30
9 years	0	0	0.19	0.19
Upper secondary	0.25	0.08	0.09	0.42
Tertiary	0,06	0,02	0.01	0.09
$\sum$	0.31	0.10	0.59	1

1990:

Level of education	Field-of-study			$\sum$
	Engineering	Business administration	”other”	
< 9 years	0	0	0.22	0.22
9 years	0	0	0.17	0.17
Upper secondary	0.29	0.09	0.10	0.48
Tertiary	0.08	0.03	0.02	0.13
$\sum$	0.37	0.12	0.51	1

1994:

Level of education	Field-of-study			$\sum$
	Engineering	Business administration	”other”	
< 9 years	0	0	0.18	0.18
9 years	0	0	0.16	0.16
Upper secondary	0.31	0.09	0.11	0.51
Tertiary	0.10	0.04	0.02	0.16
$\sum$	0.41	0.13	0.47	1

In addition to levels of education and fields-of-study we also account for the workers' age. The age structure can matter in two different ways. On the hand, an education's ”IT content” is higher the more recently the education was obtained, i.e. the younger the worker. This would point to a negative relation between age and productivity growth. On the other hand, older workers have accumulated more work experience than younger workers. If skills acquired in the workplace are more important for productivity than computer skills acquired in school, then the relation between age and productivity growth should be positive instead. To empirically assess which of these two opposing forces that dominate the other we use the following variable

$$\frac{\#\text{ 16-29 year olds}}{\#\ [(\text{16-29}) + (\text{50-74})]\text{ year olds}}\,. \tag{19}$$

The idea underlying this variable is to capture effects of relative changes in tails of the age distribution; all employees in our data belong to the age interval 16-74 years.[19] It should be noted that the ratio (19) can change even if the total number of 16-29 year olds plus the number of 50-74 year olds doesn't change. Thus, e.g., substituting a given number of older workers with an equal number of younger worker will increase the ratio.[20]

4.5 Control variables

To account for cyclical variations in TFP growth, we have used a business cycle indicator, BCI, for the Swedish manufacturing sector, cf Figure 4. The indicator together data on orders, stocks of finished goods, and expected production.[21]

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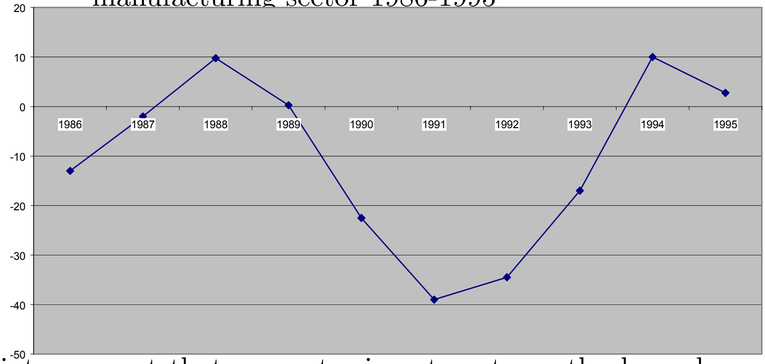
[19] In terms of years, the right tail is longer than the left tail. However, the number of people working beyond the retirement age of 65 is very small. Hence, for practical purposes the tails can be considered to be equally long.

[20] The fact that we model age structure effects by means of (19) should not be taken to mean that we deny the importance of changes in the share of 30-49 year olds for productivity growth; as shown by Malmberg (1994) workers aged 40-49 have made substantial positive contributions to growth in Sweden (along with 50-64 year olds) and Feyrer (2002) obtains similar results for a data set covering 108 different countries. However, unlike these authors we are not primarily interested in the direct link between age demographics and productivity, but on effects working via interactions between workers of different ages and IT. It is then natural to focus on the age categories that differ the most in this respect, i.e. the youngest and the oldest workers.

[21] The indicator has been constructed by the Swedish Institute for Economic Analysis (Konjunkturinstitutet).

Comparing Figure 4 and Figure 1, we see that the BCI captures the turning points in TFP growth quite well. However, the BCI cannot explain the relative magnitudes of growth at different points in time. In particular, it does not capture that TFP growth was much higher during 1991–95 than during 1986–90.[22]

Figure 4: The business cycle indicator (BCI) for the Swedish manufacturing sector 1986-1995



To take into account that computer investments partly depend on other capital investments, we include the share of non-computer equipment in total capital, K_M/K.[23] As $K_C/K + K_M/K + K_S/K = 1$ by definition, including K_M/K together with K_C/K means that we fully control for the industries' capital structures.

Finally, we include the shares of females and immigrants among the employees.Gender might be important for two reasons. Weinberg (2000) argues that computers create job openings for women by replacing physically demanding blue-collar jobs by jobs that require computer knowledge. Second, Lindbeck & Snower (2000) point out that modern work organizations are increasingly characterized by multi-tasking. If women are better

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[22] We do not want to use time dummies to control for the time variation that is common to all industries. Using time dummies amounts to eliminating the general time profile of the endogenous variable, i.e. the profile given in Figure 1. But that time profile is part of what we want to explain; one thing we want to test is whether our simple model can capture the change in the TFP growth pattern that occurred between the end of the 1980s and the beginning of the 1990s.

[23] In this respect we follow earlier studies; see, e.g., Berndt and Morrison (1995).

suited to multi-tasking than men, as is often claimed, this should favor firms with a large female labor share.

Regarding immigrants the direction of causality is more ambiguous. On the one hand, it can be conjectured that the increased international communication brought about by IT could be facilitated by a work-force comprising employees with different cultural backgrounds. On the other hand, imperfect knowledge of the host country language might have an adverse effect on productivity.

5 Results

In the first part of this section we test the empirical implications of the stylized model in Section 3, on our Swedish data. In the next subsection we consider various econometric issues. To focus on methodological aspects, the analysis is conducted within a modeling framework entailing a univariate representation of human capital. Based on our results in this section we decide upon a basic formulation of the model and an appropriate estimation method. In the last subsection we extend the basic model through multivariate specifications of human capital.[24]

Before discussing the results we will briefly comment upon three features that are common to all the regressions.

First, the estimations are based on weighted least squares (WLS), where the different industries are weighted by their shares in manufacturing employment. Methodologically we thus follow, e.g., Berman, Bound, & Griliches (1994) and Kahn & Lim (1998). The motivation for the WLS procedure can be found in the latter paper: it is reasonable to assume the

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[24] While not ideal, this sequential approach is necessary due to the fact that our data set is rather small. Considering the issues of model formulation, estimation methods, and multivariate specifications of human capital simultaneously, we would simply run out of degrees of freedom.

data for small industries to be noisier than the data for large industries. This assumption can be modeled by assuming that the standard errors of the (unweighted) residuals are inversely proportional to the square of employment. Weighting industries by employment shares will then make the residuals homoscedastic.

Second, the following control variables are always included in the regressions: the (contemporaneous) business cycle indicator, BCI, the (lagged) share of non-computer equipment capital in the total capital stock, K_M/K, and the shares of females and immigrants among the employees.

Third, we do not explicitly account for possible measurement error in the IT variable, because we lack information on this issue.

5.1 Testing the implications of the stylized model

The first point made in Section 3 was that the negative effects of IT on productivity growth reported in studies using early (pre–1990) data are not mere statistical artefacts. To see what can be said of the Swedish manufacturing sector in this respect, we estimate the following equation for the first half of our study period:

$$\text{1986-90:} \qquad g^*_{ht} \;=\; -\underset{(1.71)}{0.036} + \text{ controls} - \underset{(0.08)}{0.004} \cdot \frac{K_C}{K}_{h,t-1}, \quad R^2 = 0.18 \tag{20}$$

where absolute values of t–statistics are in parentheses.[25] The effect of IT, i.e. the coefficient of $(K_C/K)_{h,t-1}$ is negative. The theoretical analysis tells us that, although the estimate is insignificant, this indicates that IT had a negative impact on growth in Sweden, too, during the latter part of

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[25] To save space, we do not report the coefficients for the control variables here, as they are of no interest with respect to theoretical implications that we consider.

the 1980s.

The intercept is negative as expected (although insignificant). According to the theoretical analysis, this means that the observed rate of productivity growth, g^*_{ht}, underestimates the true rate, g_{ht}, by, on average, 3.6 percent; cf. (3).

The second point made in Section 3 was that if the effect of IT on productivity growth turned positive in the 1990's then we would expect, first, a positive estimate of the impact of IT when ignoring human capital variables and, second, that this positive estimate should decrease after inclusion of human capital variables. The following regression shows that the first condition is satisfied:

$$\text{1991-95:} \qquad g_{ht} = \underset{(1.83)}{-\,0.072} + \text{ controls} + \underset{(2.80)}{0.204} \cdot \frac{K_C}{K}_{h,t-1}, \qquad R^2 = 0.51 \tag{21}$$

The coefficient for $(K_C/K)_{h,t-1}$ is now positive, and strongly significant. It can also be noted that the intercept is still negative, as expected, and that it has increased in magnitude. This, too, is in line with expectations: one effect of the positive impact of IT will be quality improvements in output; to the extent that these are not captured in the data output growth and, hence, productivity growth will be (further) underestimated.

To check the second condition we include the share of workers with tertiary education as a crude proxy for skilled labor. Interacting it with K_C/K we obtain:

$$\begin{aligned} \text{1991-95:} \qquad g_{ht} &= \underset{(1.18)}{-\,0.067} + \text{ controls } + \underset{(1.02)}{0.184} \cdot \frac{K_C}{K}_{h,t-1} \\ &\quad + \underset{(0.12)}{0.066} \cdot \left(\frac{\#\,Tertiary}{\#\,Employees} \times \frac{K_C}{K} \right)_{h,t-1}, \qquad R^2 = 0.52 \end{aligned} \tag{22}$$

The inclusion of the interaction variable decreases the estimated direct effect of IT from 0.204 to 0.184, i.e. the second condition is satisfied, too. To summarize: these very simplistic regressions based on our stylized model point to a (small) negative effect on TFP in Swedish manufacturing during the second half of the 1980s and a positive effect after 1990. That is to say, they indicate a development qualitatively similar to the one experienced in the US, but with the turning point occurring somewhat earlier.

5.2 Econometric issues

In this section we will consider the following four issues: (1) the modeling of the time-varying effects of IT; cf. (5),(2) the potential presence of first-order effects of human capital on TFP growth, in addition to the second-order interaction effect given by (6), (3) industry fixed effects, and (4) serial correlation.

Our starting point is the last specification of the previous subsection, i.e. (22). We here estimate that model for the entire period of study, 1986-95, cf column I of Table 5.[26] It can be seen that in contrast to the results obtained for the 1991-95 period the point estimate of the direct effect of IT on TFP growth is negative. Thus, when the impact is not allowed to vary over time, the positive effect during 1991-95 reported in (22) is dominated by a negative impact during 1986-90.[27]

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[26] In this section we also report the estimates obtained for the control variables.

[27] This is verified when we apply the specification used in (22) to data for 1986-90. This yields an estimate of the direct effect of IT that is equal to -0.314 and significant at the 1 % level.

Table 5: Alternative model specifications, given univariate measure of human capital

Dependent variable: g_{ht}	I	II	III	IV	V
Intercept	-0.0239 (0.976)	-0.0515 (2.720)	-0.0471 (2.313)	0.0974 (0.894)	-0.0545 (3.207)
Control variables:					
BCI_t	0.0002 (2.046)	0.0003 (2.569)	0.0003 (2.526)	0.0002 (1.094)	0.0003 (2.697)
$\left(\frac{K_M}{K}\right)_{h,t-1}$	0.0880 (2.133)	0.1179 (3.181)	0.1072 (2.259)	0.1478 (1.998)	0.1245 (3.644)
$\left(\frac{\# Females}{\# Employees}\right)_{h,t-1}$	0.0104 (0.325)	0.0010 (0.313)	0.0121 (0.371)	-0.3340 (1.394)	0.0078 (0.267)
$\left(\frac{\# Immigrants}{\# Employees}\right)_{h,t-1}$	-0.3010 (2.334)	-0.1868 (1.327)	-0.1972 (1.369)	-0.5453 (1.581)	-0.1586 (1.225)
Direct effect of IT:					
$\left(\frac{K_C}{K}\right)_{h,t-1}$	-0.0875 (1.009)				
$\left[TUITE \times (\frac{K_C}{K})_h\right]_{t-1}$		0.0002 (1.430)	0.0002 (1.441)	-0.0001 (0.483)	0.0002 (1.948)
Direct effect of human capital:					
$\left(\frac{\# Tertiary}{\# Employees}\right)_{h,t-1}$			0.0349 (0.363)		
IT and human capital interaction:					
$\left(\frac{\# Tertiary.}{\# Employees} \times \frac{K_c}{K}\right)_{h,t-1}$	1.0826 (3.276)	0.4961 (1.957)	0.3248 (0.606)	1.3426 (1.973)	0.4225 (1.798)
Industry dummies	No	No	No	Yes[a]	No
Correction for AR(1) residuals	No	No	No	No	Yes[b]
R^2	0.34	0.34	0.34	0.44	0.39

aThe reference industry is 3100 = Food, Beverages and Tobacco.

b Iterative Parks (1967) procedure, second-round estimates.

Having thus established the need for a time-varying effect, we turn to the first issue, the specification of an explicit form for the function $\psi\,(TUITE)_{t-1}$. We have chosen to approximate ψ by a linear function since our data only cover ten years, making it difficult to precise estimate higher order approximations:

$$\psi\left(TUITE\right)_{t-1} = \gamma \cdot TUITE_{t-1}\,; \qquad \gamma > 0, \tag{23}$$

where γ is a parameter and $TUITE$ the index described in Section 4.3.[28]

The effect of incorporating (**??**) can be assessed by comparing columns I and II in Table 5. It is clear that all the parameter estimates are affected. In particular, the point estimate of the direct effect of IT changes from -0.0875 to 0.0002. And while the indirect effect decreases, the two changes do not cancel each other out; the partial derivative of $g_{h,t}$ with respect to $(K_C/K)_{h.t-1}$ [cf. (8)] increases in magnitude. As the time-varying specification is in line with our theoretical model and does have an impact, we will stick to it in the following.

The next issue concerns the possibility of direct, first-order, effects of human capital on $g_{h,t}$. While our theoretical analysis does not imply that human capital should have a direct effect on growth – cf. footnote 10 – there might still be empirical grounds for such a direct effect. To assess this possibility we compare columns II and III in Table 5, which differ only by the inclusion of the human capital variable in column III. It can be seen that the direct effect of human capital is small and very imprecisely estimated. With respect to the other estimates, the only one affected is the coefficient measuring the indirect, interaction, effect. That coefficient becomes smaller and insignificant. Taken together, it appears that the

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[28] A disadvantage with the linear form is that it cannot allow the effect of IT on TFP growth to change sign over time. As a result, the partial derivative (8) cannot be negative, under the assumptions made in Section 3. However, when we turn to a multivariate specification of human capital, in Section 5.3, there is no reason to restrict all the IT and human capital interaction effects to be positive. The partial derivative of TFP growth with respect to IT might then change sign over time. It will be seen that this does indeed happen in our estimations.

inclusion of a direct human capital effect has the clear disadvantage of creating multicollinearity problems but no discernible empirical advantage. Henceforth, we will therefore not consider direct effects of human capital.

The third issue, allowing for industry fixed effects amounts, in this context, to allow for cross-industry differences in the expected mismeasurement in output, cf. (3). While desirable, this generalization is quite costly in terms of degrees of freedom. Comparing columns II and IV in Table 5, we see that allowing for industry fixed effects results in the estimate of the direct effect of IT becoming less significant, both economically and statistically, while the economic significance of the indirect effect is substantially increased. The fixed effects themselves take on implausible values, however. For industry 3100 = Food, Beverages and Tobacco, which is the reference industry, the fixed effect is given by the intercept. While insignificant, the estimate of the intercept says that the mismeasurement in output in industry 3100 is such that, on average, the (true) rate of productivity growth is *overestimated* by 9.7 percent. For the other industries, the fixed effects are given by deviations from the reference level of 9.7 percent, determined by means of estimated coefficients on industry dummies. These coefficients imply that the estimated fixed effects are positive for all the other industries as well.[29] As we find it really hard to believe that IT has resulted in TFP growth being overestimated in every industry we will disregard industry-specific fixed effects from now on.

The issue of serial correlation, finally, is important because the interpretation of the lagged explanatory variables as predetermined is valid

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[29] The coefficients, which should be added to the intercept, are, by industry, 3200: 0.0693, 3300: -0.0684, 3400: -0.0526**, 3500: -0.0262, 3600: -0.0901*, 3700: -0.0766, 3810: -0.0600, 3820: -0.0879, 3830: -0.0211, 3840: -0.0838, 3850: -0.0841*, 3860: -0.0934, 3900: 0.0193, where * and ** denote significantly different from zero at the 10 and 5 % level, respectively.

only if the regression residuals fulfill the assumption of being random disturbances and, hence, not correlated over time. As our panel only covers a ten-year period, formal tests for autocorrelation will, unfortunately, have very low power. Nevertheless, it is possible to estimate the parameters of a simple autoregressive structure. To this end we apply an iterated version of the procedure suggested by Parks (1967) to correct for first-order autocorrelation in a multiple-equation context. The assumed autocorrelation structure is given by:

$$u_{h,t} = \rho_h u_{h,t-1} + e_{h,t}\,, \qquad |\rho| < 1 \tag{24}$$

where the $e_{h,t}$ are white noise disturbances. Note that the autocorrelation parameter, ρ, is allowed to vary across industries. We apply this structure to the model given by column II in Table 5. The first-round estimates of the ρ_h are obtained by application of (24) to the estimated residuals of the column II specification. All 14 estimates fulfill the requirement that $|\rho| < 1$. As judged from the t-statistics, only one estimate is signifantly different from zero, at the 10 % level. Still, the first-round estimates, denoted by $\widehat{\rho}_{1h}$, are used to estimate the model:

$$y^*_{h,t}\left(\widehat{\rho}_{1h}\right) = \mathbf{x}^*_{h,t}\left(\boldsymbol{\beta}, \widehat{\rho}_{1h}\right) + u^*_{h,t}\widehat{\rho}_{1h} \tag{25}$$

where

$$\begin{aligned}
y^*_{h,t}\left(\widehat{\rho}_{1h}\right) &= \left(1-\widehat{\rho}_{1h}\right)^{\frac{1}{2}} y_{h,t}\,, && \text{for} \quad t = 1986 \\
y^*_{h,t}\left(\widehat{\rho}_{1h}\right) &= y_{h,t} - \widehat{\rho}_{1h} \cdot y_{h,t-1}\,, && \text{for} \quad t = 1987, ..., 1995 \\
\mathbf{x}^*_{h,t}\left(\boldsymbol{\beta}, \widehat{\rho}_{1h}\right) &= \left(1-\widehat{\rho}_{1h}\right)^{\frac{1}{2}} \mathbf{x}^*_{h,t}\left(\boldsymbol{\beta}\right)\,, && \text{for} \quad t = 1986 \\
\mathbf{x}^*_{h,t}\left(\boldsymbol{\beta}, \widehat{\rho}_{1h}\right) &= \mathbf{x}_{h,t} - \widehat{\rho}_{1h} \cdot \mathbf{x}_{h,t-1}\,, && \text{for} \quad t = 1987, ..., 1995
\end{aligned} \tag{26}$$

the 1986 variables being constructed according to the Prais-Winsten transformation. The resulting $\boldsymbol{\beta}$-estimates were qualitatively similar to the ones in column II of Table 5 with small differences in magnitude and significance.

By means of the $u^*_{h,t}\left(\widehat{\rho}_{1h}\right)$, second-round estimates $\widehat{\rho}_{2h}$ were obtained. Two of these estimates were significantly different from zero at the 10 % level, thus indicating no improvement with respect to autocorrelation, as compared to the original specification (where only one of the estimated autocorrelation parameters was significantly different from zero at the 10 % level). The estimate of the vector $\boldsymbol{\beta}$ obtained from the regression model transformed by means of the $\widehat{\rho}_{2h}$ was extremely close to the original $\boldsymbol{\beta}$ estimate; compare columns V and II in Table 5. From the table it can be seen that the t-statistics are very close, too. But again, there was no discernable improvement with respect to the residuals; of the $\widehat{\rho}_{3h}$ estimates one was significant, at the 5 % level. Upon further iterations, the initial pattern was repeated: the estimates of the structural parameters shifted back and forth between one alternative similar to the original column II specification and one alternative extremely close to this specification. In no case was there any improvement with respect to the serial correlation of the residuals, as compared to the column II specification. Thus, there is no strong indication that the residuals of the model in column II of Table 5 are autocorrelated and application of a standard procedure to correct for possible autocorrelation has no effect on the parameter estimates and and seems to make the residuals less well-behaved.

Based on the results of this section we conclude that, in line with the theoretical arguments in Section 3, it seems important to allow the effects of IT to vary over time. We do not find that our modeling framework needs to be extended to account for the other three issues that we have considered – potential first-order effects of human capital on TFP growth, industry fixed effects, and serial correlation. Using specification II in Table 5 as our starting point we now proceed to consider more detailed, multivariate specifications of human capital.

5.3 Multivariate specifications of human capital

Apart from indicating the need for relative measures (cf. Section 4.2) theory does not provide any guidance regarding the implementation of a more detailed specification of human capital. We have constructed variables such that the model can tell the effects of marginal changes in the educational structure.

The effect that we are interested in is given by the partial derivative of total factor productivity growth with respect to this measure:

$$\frac{\partial g_{ht}}{\partial \left(K_C/K\right)_{h,t-1}} = \sum_{i=1}^{m} \widehat{\theta}_i \cdot X_i \tag{27}$$

where $\widehat{\theta}_j$ denotes an estimated coefficient and X_j represents an associated human capital variable. The variance of this partial derivative is equal to

$$Var\left[\frac{\partial g_{ht}}{\partial \left(K_C/K\right)_{h,t-1}}\right] = \sum_{i=1}^{m} X_i^2 \cdot Var\left(\widehat{\theta}_i\right) + 2\sum_{i=1}^{m}\sum_{j>i}^{m} X_i X_j Cov\left(\widehat{\theta}_i \widehat{\theta}_j\right) \tag{28}$$

As the variance computation is a bit complicated we will, to begin with, merely consider the individual terms in (27), implying that we only have to consider the corresponding $t-$ ratios.

Table 6: Growth regressions allowing for externalities in the use of IT

Dependent variable: g_{ht}	I	II	III
Intercept	-0.0273 (1.132)	-0.2440 (0.952)	-0.0225 (1.226)
Control variables:			
BCI_t	0.0002 (2.082)	0.0002 (1.902)	0.0002 (2.000)
$\left(\frac{K_M}{K}\right)_{h,t-1}$	0.0586 (1.426)	0.0545 (1.168)	0.0547 (1.753)
$\left(\frac{\#\,Females}{\#\,Employees}\right)_{h,t-1}$	0.0201 (0.592)	-0.0021 (0.051)	
$\left(\frac{\#\,Immigrants}{\#\,Employees}\right)_{h,t-1}$	0.0159 (0.110)	0.0440 (0.205)	
Direct effect of IT:			
$\left[TUITE \times (\frac{K_C}{K})_h\right]_{t-1}$	0.00006 (0.505)	0.00001 (0.096)	
Direct effect of human capital:			
$\left(\frac{\#Tertiary}{\#(Upper\ sec.+Tertiary)} \times (\frac{K_C}{K})\right)_{h,t-1}$	0.6460 (2.061)		
$\left[\frac{\#Tertiary\ Engineers}{\#(Upper\ sec.+Tertiary\ Engineers)} \times \frac{K_c}{K}\right]_{h,t-1}$		0.8497 (3.413)	0.8779 (5.289)
$\left[\frac{\#Tertiary\ Business\ adm.}{\#(Upper\ sec.+Tertiary\ Bus.\ adm.)} \times \frac{K_c}{K}\right]_{h,t-1}$		-0.8646 (2.039)	-0.8324 (2.383)
$\left[\frac{\#Tertiary\ "Other"}{\#(Upper\ sec.+Tertiary\ "Other")} \times \frac{K_c}{K}\right]_{h,t-1}$		0.9498 (1.198)	0.8779 (5.289)
$\left[\frac{\#Upper\ sec.}{\#(9\ years+Upper\ sec.)} \times \frac{K_c}{K}\right]_{h,t-1}$	0.4240 (1.812)	0.9104 (2.996)	0.8779 (5.289)
$\left[\frac{\#16\text{-}29\ year\ olds}{\#(16\text{-}29+50\text{-}74\ year\ olds)} \times \frac{Kc}{K}\right]_{h,t-1}$	-0.8122 (3.464)	-1.2996 (3.393)	-1.2593 (5.877)
R^2	0.403	0.437	0.437

Table 6 reports the results of three different specifications. In column I we have allowed for the possiblity that, in addition to tertiary educated workers, employees with upper secondary education also belong to the firm's skilled workers.

The number of employees with tertiary education has been related to the number of employees with upper secondary or tertiary education. Similarly, the number of upper secondary educated workers has been normalized by the number of workers with 9 years of education or upper secondary education. We also use the variable (19) to account for the age structure aspect of human capital.

Clearly, accounting for upper secondary education and the age structure are important extensions. The corresponding parameter estimates are strongly significant. Interestingly, the indirect effect of IT associated with the age structure is negative. This implies that the negative effect of lost work experience caused by old workers retiring outweighs the positive effect of the entry of young workers with high ”IT content” in their basic education. Comparing column I of Table 6 with column II of Table 5 we see that the more detailed modeling of human capital renders the estimated direct effect of IT smaller and that among the control variables only the business cycle indicator stays significant.

The next step is to disaggregate the measures of human capital even further, by fields of study; cf. column II of Table 6. We find considerable differences across fields. In particular, while there is a positive indirect effect of IT associated with the relation between engineers with university education and engineers with upper seconday education there is a negative indirect effect connected with the corresponding categories in business administration. While the this difference is somewhat counter-intuitive, there are results in the literature that point in this direction. For example, Murphy et al. (1991) claim that while "entrepreneurs" affect growth positively "rent-seekers" are harmful to growth. Proxying entrepreneurs and rent-seekers with engineers and lawyers, respectively, they find empirical support for their claim. As our category Business administrators includes lawyers, this finding is relevant for our results. Further, Mellander and Skedinger (1999) show that in the mid 1990s wage premia for university education were much higher among business administrators than engineers in seven European countries, including Sweden, in spite of an engineering degree requiring more years of study. A possible interpretation is that the university wage premium for business administrators is ”too high”, relative to their contribution to productivity.

The see if the regression model in column II can be expressed in a more parsimonious way, we test the following composite hypothesis:

(i) The coefficients of $\left[TUITE \times \left(\frac{K_C}{K}\right)_h\right]_{t-1}$, $\left[\frac{\textit{\#Females}}{\textit{\#Employees}}\right]_{h,t-1}$ and $\left[\frac{\textit{\# Immigrants}}{\textit{\# Employees}}\right]_{h,t-1}$ are zero.

(ii) The coefficients of $\left[\frac{\textit{\# Tertiary Engineers}}{\textit{\# (Upper sec. + Tertiary Engineers)}} \times \frac{K_C}{K}\right]_{h,t-1}$, $\left[\frac{\textit{\# Tertiary ”Other”}}{\textit{\# (Upper sec. + Tertiary ”Other”)}} \times \frac{K_C}{K}\right]_{h,t-1}$ and $\left[\frac{\textit{\# Upper sec.}}{\textit{\# (9 years + Upper sec.)}} \times \frac{K_C}{K}\right]_{h,t-1}$ are equal .

With respect to hypothesis ii) it should be emphasized that equality among the coefficients does *not* imply that the associated indirect effects of IT on productivity growth are equal. If the coefficients are equal, the corresponding indirect effects will be determined by the relative magnitudes of the human capital variables. Among these, the ratio $\frac{\textit{\# Upper sec.}}{\textit{\# (9 years + Upper sec.)}}$ is invariably the largest.

As indicated by the fact that there is no difference between the R^2 s in columns II and III, the composite hypothesis cannot be rejected at any standard level of significance. We thus end up with a model containing only six parameters, which explains 44 percent of the variation in total factor productivity growth across industries and over time!

What, then, are the relative magnitudes of the indirect effects in our preferred specification, i.e. column III in Table 6? For the manufacturing sector as a whole this question can be answered by means (5.8) and Table 4. The largest positive indirect effect is the one associated with the ratio $\frac{\#\ \textit{Upper sec.}}{\#\ \textit{(9 years + Upper sec.)}}$; for a marginal increase in the share of computers in total capital the effect varies between 0.60 percentage points in 1986 and 0.67 percentage points in 1995. The largest negative indirect effect, which is the one channeled through the age structure, i.e. the ratio $\frac{\#\ \textit{16 – 29 year olds}}{\#\ \textit{(16 - 29 + 50 - 74 year olds)}}$, decreases in magnitude over time, from -0.68 percentage points in 1986 to 0.60 percentage points in 1995.[30]

The next to largest positive indirect effect is associated with the relation between university educated engineers and engineers with upper secondary education, the ratio $\frac{\#\ \textit{Tertiary Engineers}}{\#\ (\textit{Upper sec. + Tertiary Engineers})}$; the indirect effect increases from 0.17 percentage points in 1986 to 0.21 percentage points in 1995. This effect is however offset by the negative indirect effect connected to business administrators, which decreases from -0.17 percentage points in 1986 to -0.26 percentage points in 1995. Finally, a positive indirect effect stemming from the relation between employees with "other" university and upper secondary education, respectively, makes upp the balance: this positive effect increases from 0.09 percentage points in 1986 to 0.14 percentage points in 1995.

While these results for the entire manufacturing sector provide a gen-

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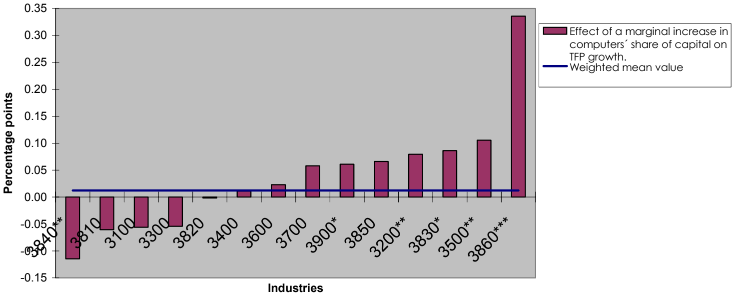
[30] To save space, the age structure data have not been provided in Section 4.4. However, for the years 1985 and 1994 the age structure ratio is equal to 0.536 and 0.479, respectively, reflecting a declining inflow of young people and ageing of the incumbents.

eral feeling for the time profile of the effect of IT on total factor productivity growth, an important feature of the model is that it allows the effect of marginal increases in computers' share to vary over time and by industries. This is illustrated in Figures 5a–c, which are based on computations using specification III in Table 6. The diagrams show the distributions of the partial derivatives (5.8) across industries at three points in time, 1986, 1991 and 1995. The estimates' precision have been computed according to (5.9).The estimates can be interpreted as answering the following question: If the share of computers in total capital increases by 1 percent, what is the resulting change in the rate of growth in total factor productivity, in percentage points? The bars indicate the effects for individual industries. The solid line is a weighted average effect, where the industries are weighted by their employment shares.

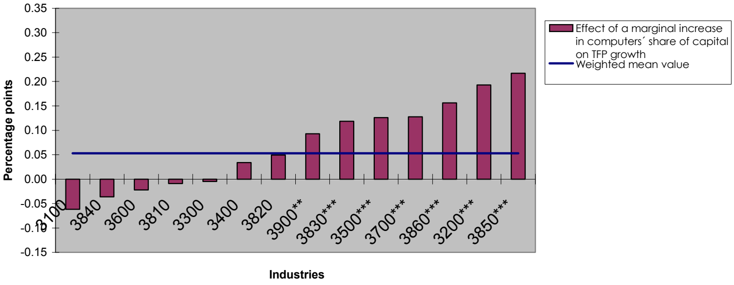
Looking at the development over time, we see that the marginal effects of computer investments have increased steadily over time. The weighted average effect rises from about 0.01 percentage point in 1986 to 0.05 in 1991, ending up at 0.17 percentage points in 1995. These average changes have been caused by upward shifts in the entire distributions of effects across industries. For instance, while only two industries record effects above $\frac{1}{10}$ of a percentage point in 1986, effects of this magnitude are found in six industries in 1991 and in 11 in 1995. In the latter year, the point estimates are 0.25 or higher in five industries, indicating that a 1 percent increase in computers' share in total capital increases the rate of TFP growth by $\frac{1}{4}$ of a percentage point or more.

Figure 5: Distributions over industries of the effects of a marginal increase in computers´ share of capital on TFP growth; regression III in Table 6, evaluated in 1986, 1991 and 1995.

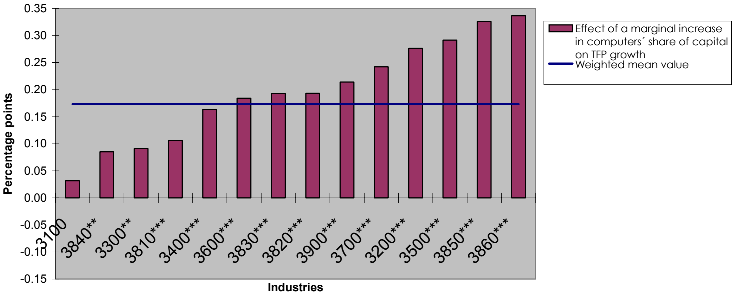
a:1986



b:1991



c:1995



Note: Stars indicate significance level: "*" denoting 10 percent, "**" 5 percent and "***" 1 percent.

Among the three years covered by Figure 5a–c, the largest variation across industries is found in 1986. In that year the spread is 0.46 percentage points, the range being given by a negative effect of −0.12 percentage points in 3840 = Transportation and a positive effect of 0.34 percentage points in 3860 = Shipyards.[31] In 1991 and 1995 the spread is considerably smaller – about 0.30 percentage points in both years. Moreover, in 1995 the effects are positive in *all* industries. There are thus two findings pointing to a fundamental difference between the beginning and the end of the period that we study: compared to 1986 the variation across industries is smaller in 1995 *and* the estimated effects are confined entirely to the positive domain, unlike 1986 when about a third were negative.

In line with our basic hypothesis of the importance of human capital, a comparison of Figure 5 and Table 3 shows that the industries that had the largest increases in the shares of computers in total capital were not in general the industries that had the largest growth-enhancing effects of IT. For instance, the industries 3300 = Saw Mills and Wood Products and 3700 = Basic Metals increased the relative size of their computer capital stock dramatically between 1985 and 1990; cf Table 3. These investments did not result in top-ranking marginal effects of IT in either 1991 or 1995, however; see Figure 5. Conversely, industry 3850 = Instruments, Photographic & Optical Devices experienced very large IT-induced growth effects in 1991 and 1995. In this industry the share of computers *decreased* between 1985 and 1990 – cf Table 3. Instead, the share of skilled workers increased strongly in this industry.[32]

Finally, a notable result is that, compared to the U.S., we find positive impacts of IT on growth in a broader spectrum of industries. According to

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[31] The shipyards rank very high in 1991 and 1995, too. Since the Swedish shipyards have undergone major structural changes since the mid 70's and have been facing severe problems with low and, sometimes, negative profits this industry could be seen as a potential outlier. To check this, we reestimated the model given by column III in Table 6, leaving out the shipyards. The parameters changes were entirely negligible, however. The reason is the WLS estimation procedure where the industries are weighted by employment; the shipyards account for less than 1 percent of manufacturing employment, during the period studied.

[32] The latter fact cannot be inferred from the paper but can be seen when the Table 4 is broken down by industry.

Gordon (2000), in the U.S. the effects of computer investments were essentialy zero outside the IT-producing industries and the industries producing durable manufacturing goods. In the Swedish manufacturing sector, these industries roughly correspond to: 3810, 3820, 3830, 3840, 3850, and 3860; see Table 2. From Figure 5 it can be seen that while we find large marginal effects in some of these industries, notably in 3850 = Instruments and 3860 = Shipyards, we also see examples of negative or very small effects as in, e.g., in 3810 = Metals and 3840 = Transportation. On the other hand, there are several industries outside this group recording large positive effects like 3200 = Textiles and 3500 = Chemicals.[33]

Table 7: Statistics for non-nested tests of the presence of K_c/K in growth equation; critical value at 1% significance level ±2.57

	Model	
	I	II
H_o: include K_c/K H_a: exclude K_c/K	-0.329	-0.686
H_o: exclude K_c/K H_a: include K_c/K	3.193	4.112

Note: i) the model specifications refer to the columns in Table 6
ii) "include K_c/K" refers to the regressions in Table 6 while "exclude K_c/K" means setting K_c/K=1 in those regressions
iii) the test statistic is asymptotically normally distributed.

However, while our results certainly seem to indicate that the human capital variables are essential, one might wonder about the importance of the computer capital share, K_c/K. Is this variable really essential, too, or can the human capital variables do the job by themselves? This is an important question because our interpration of human capital being the key to the IT productivity paradox relies on the assumption that it

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[33] Using more recent U.S. data than Gordon (op.cit) and dummy variable techniques, Stiroh (2002) finds indications of substantial effects of IT after 1995 not only in industries producing IT and durable goods, but also in IT-intensive industries, defined as industries having above median shares of computers in total capital. He does not link these findings to human capital structures, however.

is the *interaction* between K_c/K and human capital that matters. To check if this is the case it is necessary to conduct a non-nested test of whether K_c/K should be included in the growth equations or not. To this end we use the J test proposed by Davidson and MacKinnon (1981). The results of applying this test to the specifications I and II in Table 6 are given in Table 7. Note that the results concern the testing of *two* hypotheses. An intrinsic feature of a non-nested test is that there is no natural null hypothesis. Being a specification test, the non-nested test merely investigates how two alternative models fit the data.

In the first row of Table 7 we provide the test statistics for the case when the specifications in Table 6 constitute the null hypotheses. The alternative, $\mathrm{H_a}$, corresponds to when $K_c/K = 1$ in the regressions. In none of the tests can the null be rejected at any standard level of significance.

In the second row, the roles of the null hypothesis and the alternative hypothesis have been reversed. The null is very clearly rejected in favor of the alternative.

These results provide strong evidence for the model specifications in Table 6 and reject the alternative specifications where $K_C/K = 1$. Put differently, the outcomes give convincing support for the notion that it is the interaction between IT capital and human capital that drives our results. This conclusion is further strengthened by the fact that it is quite unusual that non-nested tests yield results as clear as in this case; often the tests produce inconsistent results (reject both of the null hypotheses) or inconclusive results (reject neither).[34]

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[34] The reason why we have not performed the test on specification III in Table 6 is that the Davidson-MacKinnon test cannot be applied to models incorporating linear constraints. Pesaran and Hall (1998) discuss non-nested tests allowing for general linear restrictions. However, given the very clear outcomes of the tests reported in Table 7 and the fact that, statistically, the specifications II and III in Table 6 are very close we have not taken the trouble to formulate such a general test.

6 Summary and conclusions

Our principal conclusion from this study is that human capital is the key to the IT productivity paradox. We substantiate this general conclusion with both theoretical and empirical results.

Our theoretical analysis investigates the consequences of erroneously disregarding human capital aspects in assessments of the effects of IT on productivity growth. Specifically, we consider a model where IT affects growth both directly and indirectly, through complementarity with human capital, and analyze what happens to the estimate of the direct effect when the indirect effect is omitted.

Regarding the negative effects of IT on growth reported in several studies using early (pre–1990) U.S. data, our conclusion is that these results are likely to indicate a truly negative effect, as suggested by Morrison (1997), rather than be a consequence of measurement error, as argued by, e.g., Lee and Barua (1999).

The positive relation between IT and productivity growth found in studies based on more recent data is in our theoretical analysis attributed to positive external effects in the use of IT. These external effects are assumed to be increasing in the total use of IT, implying that as more and more IT capital is accumulated, the growth effects change from negative to positive.

In the empirical analysis, we first confirm that the predictions generated in the theoretical analysis are valid for our data on the Swedish manufacturing sector. We then proceed to include successively more information about interactions between IT and human capital. As shown by the theoretical analysis, accounting for indirect effects of IT in this way reduces the estimated direct effect. Eventually, the direct effect finally vanishes altogether.

We end up with a model that is very parsimonious in terms of parameters but, nevertheless, explains well over 40 percent of the variation in total factor productivity growth across industries and over time. In this model, all the interaction variables between IT and human capital are highly significant.

In general, the maintained hypothesis of complementarity between IT and skilled workers is confirmed. The largest indirect effects of IT on growth are associated with workers having upper secondary education, relative to workers with only 9 years of education. Disaggregating by fields of study, we find the next to largest effect to be associated with the relation between university educated engineers compared to engineers with upper secondary education.

An exception to the complementarity relation between IT and skilled labor concerns workers within the field of business administration and law. For these, the relation between university educated and workers with upper secondary education gives rise to a negative indirect impact on productivity growth. In the spirit of Murphy et al. (1991), we interpret the negative estimate as indicating rent-seeking behavior among business administrators and lawyers.

Regarding the connection between human capital and the age structure we find that replacing workers aged 50 or older by workers below 30 has a negative impact on productivity growth rates. This indicates that, during the period studied, the advantage of many of the younger workers of having become acquainted with IT during their school years did not outweigh the work experience acquired by the older workers. This negative indirect effect is quite large but decreasing, due to a declining inflow of young people to the manufacturing sector.

For the manufacturing sector as a whole, the model predicts that in the beginning of the period, in 1986, a 1 percent increase in the share of computers in total capital increased productivity growth by 0.01 percentage points only, i.e. an entirely negligible effect. In the middle of the period, in 1991, this average effect had grown to 0.05 percentage points, while at the end of the period, in 1995, it was up to 0.17 percentage points.
The variation in effects across industries decreases over time. Moreover, while the effects of IT on growth are negative in several industries in 1986, the effects are positive in all industries in 1995. In five of them the estimated effect was 0.25 or higher, saying that a 1 percent increase in computers' capital share increased productivity growth by at least $\frac{1}{4}$ of a percentage point.

To check that our results are not driven solely by human capital developments but by complementarity between IT and human capital, we perform non-tested tests for the presence of the IT variable in the growth equations. These tests provide very strong support for the complementarity hypothesis.

In line with our basic hypothesis, we find that the industries were the (relative) increases in computer capital have been particularly large are not necessarily the industries that show the largest marginal effects of IT on productivity growth.

With respect to differences in effects across industries, we also relate our findings to the claim in Gordon (2000) that IT has increased productivity growth only in a small number of U.S. industries. We show that, unlike in the U.S., the Swedish IT development has had positive effects outside the sectors producing IT and durable manufacturing goods. We find strongly positive effects also in, e.g., the chemical industry and, even more interesting, in the textile industry.

Regarding policy considerations, one conclusions is immediate: measures to promote increased use of IT should be followed up by measures promoting skill upgrading, especially from elementary to upper secondary education. Another implication is that measures aimed at facilitating early retirement among older workers, in order to make more room for young labor market entrants, can be (strongly) harmful for growth.

It should be remembered, however, that our study is based on data ending quite a few years back. Our results on the age structure might have changed during recent years. Investigating whether this is the case is an important task for future research. Also, it should be noted that our findings concern only the manufacturing sector and cannot be extended to the service sector or the economy as a whole. While analyses of the service and the entire economy lie beyond the scope of the present paper because of data limitations, we believe that such analyses are important tasks for future research.

References

[1] Aghion, P. & P. Howitt (1992) ”A Model of Growth through Creative Destruction”, *Econometrica*, Vol. 60, pp. 323–351.

[2] Autor, D.H., L.F. Katz, & A.B. Kreuger (1998) ”Computing Inequality: Have Computers Changed the Labor Market?”, *Quarterly Journal of Economics*, Vol. CXIII, pp. 1169-1213.

[3] Barro, R.J. & X. Sala–i–Martin (1999) *Economic Growth*, MIT Press, Cambridge, Massachusetts, U.S.A.

[4] Basu, S., J.G. Fernald, N. Oulton, & S. Srinivasan (2003) ”The Case of the Missing Productivity Growth: Or, Does Information Technology Explain Why Productivity Accelerated in the United States but not the United Kingdom?” *NBER Macroeconomics Annual 2003*

[5] Benhabib, J. & M.M. Spiegel (1994) ”The Role of Human Capital in Economic Development: Evidence from Aggregate Cross-Country Data”, *Journal of Monetary Economics*, Vol. 34, pp. 143-173.

[6] Berman, E., J. Bound, & Z. Griliches (1994) ”Changes in the Demand for Skilled Labor within U.S. Manufacturing: Evidence from the Annual Survey of Manufactures”, *Quarterly Journal of Economics*, Vol. CIX, pp. 367–398.

[7] Berndt, E.R., Z. Griliches & N.J. Rappaport (1995) ”Econometric Estimates of Price Index for Personal Computers”, *Journal of Econometrics*, Vol. 68, pp. 243-268.

[8] Berndt, E.R. & C.J. Morrison (1995) ”High–tech capital formation and Economic Performance in U.S. manufacturing industries: An exploratory analysis”, *Journal of Econometrics*, Vol. 65, pp. 9–43.

[9] Berndt, E.R. & N.J. Rappaport (2001) "Price and Quality of Desktop and Mobile Personal Computers: A Quarter-Century Historical Overview", *American Economic Review, Papers and Proceedings*, Vol. 91, pp. 268–273.

[10] Bresnahan, T.F., E. Brynjolfsson, & L.M. Hitt (2002) ”Information Technology, Workplace Organization, and the Demand for Skilled

Labor: Firm–Level Evidence", *Quarterly Journal of Economics*, Vol. CXVII, pp. 339–376.

[11] Bresnahan, T.F. & M. Trajtenberg (1995) "General Purpose Technologies: 'Engines of Growth'?", *Journal of Econometrics*, Vol. 65, pp. 83-108.

[12] Brynjolfsson, E. (1993) "Information Technology and the Productivity Paradox: Review and Assessment", *Communications of the ACM*, Vol. 35, pp. 66–77.

[13] Caves, D.W., L.R. Christensen, & W. E. Diewert (1982) "The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity", *Econometrica*, Vol. 50, pp. 1393–1414.

[14] David, P. A. (1990) "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox", *American Economic Review, Papers and Proceedings*, Vol. 80, pp. 355–361.

[15] Davidson, R. & J. MacKinnon (1981) "Several Tests for Model Specification in the Presence of Alternative Hypotheses", *Econometrica*, Vol. 49, pp. 781-793.

[16] Dean, E.R. (1999) "The Accuracy of the BLS Productivity Measures", *Monthly Labor Review*, pp. 24-34.

[17] Feyrer, J.D. (2002) "Demographics and Productivity", mimeo, Dept. of Economics, Dartmouth College.

[18] Gordon, R.J. (2000) "Does the 'New Economy' Measure up to the Great Inventions of the Past?", *Journal of Economic Perspectives*, Vol. 14, pp. 49-74.

[19] Greenwood, J. & M. Yorukoglu (1997) "1974", *Carniege-Rochester Series on Public Policy*, Vol. 46, pp. 49-95.

[20] Griliches, Z. (1969) "Capital-Skill Complementarity", *Review of Economics and Statistics*, Vol. LI, pp. 465–468.

[21] Harris, S. E.& J. L. Katz (1991) "Organizational Performance and Information Technology Investment Intensity in the Insurance Industry", *Organizational Science*, Vol. 2, pp. 263–296.

[22] Helpman, E. & M. Trajtenberg (1998) "A Time to Sow and a Time to Reap: Growth Based on General Purpose Technologies", in E. Helpman (ed.): *General Purpose Technologies*, MIT Press.

[23] Jones, C.I. (1995) "R&D-based Models of Economic Growth" *Journal of Political Economy*, Vol. 103, pp. 759–784.

[24] Jones, C.I. (1999) "Growth: With or Without Scale Effects" *American Economic Review, Papers and Proceedings*, Vol. 89, pp. 139–144.

[25] Jorgenson, D.W. (2001) "Information Technology and the US Economy", *American Economic Review*, Vol. 91, pp. 1–32.

[26] Jorgenson, D.W., L.R. Christensen, & L.J. Lau (1973) Transcendental Logarithmic Production Frontiers", *Review of Economics and Statistics*, Vol. 55, pp. 28–45.

[27] Jorgenson, D.W. & K.J. Stiroh (2000) "Raising the Speed Limit: U.S. Economic Growth in the Information Age", *Brookings Papers on Economic Activity*, pp. 125–211.

[28] Kahn, J.A. & J.–S. Lim (1998) "Skilled Labor–Augmenting Technical Progress in U.S. Manufacturing", *Quarterly Journal of Economics*, Vol. CXIII, pp. 1281–1308.

[29] Kaiser, U.(2003) "Strategic Complementarities Between Different Types of ICT-Expenditures", ZEW Discussion Paper No 03-46.

[30] Lam, D. & R. F. Schoeni (1993) "Effects of Family Background on Earnings and Returns to Schooling: Evidence from Brazil", *Journal of Political Economy*, Vol. 101, pp. 710–740.

[31] Lee, B. & A. Barua (1999) "An Integrated Assessment of Productivity and Efficiency Impacts of Information Technology Investments: Old Data, New Analysis and Evidence", *Journal of Productivity Analysis*, Vol. 12, pp. 21–43.

[32] Lindbeck, A. & D.J. Snower (2000) "Multi-Task Learning and the Reorganization of Work: From Tayloristic to Holistic Organization", *Journal of Labor Economics*, Vol. 18, pp. 353–376.

[33] Loveman, G.W. (1988) ”An Assessment of the Productivity Impact of Information Technologies”, in T.J. Allen and M.S.S. Morton (eds): *Information Technology and the Corporation of the 1990s: Research Studies,* Cambridge, MA: MIT Press.

[34] Lucas, R. (1990) ”Why Doesn´t Capital Flow from Rich to Poor Countries?”, *American Economic Review*, Vol. 80, pp. 92-96.

[35] Malmberg, B. (1994) ”Age Structure Effects on Economic Growth – Swedish Evidence”, *Scandinavian Economic History Review*, Vol. XLII, pp. 279-295.

[36] Mellander, E. (1999) ”The Multi–Dimensional Nature of Technical Change and Skill–Biased Technical Change”, IUI Working Paper No 518.

[37] Mellander, E. & P. Skedinger (1999) ”Corporate Job Ladders in Europe: Wage Premia for University vs High School–Level Jobs”, *Swedish Economic Policy Review,* Vol. 6, pp. 449–487.

[38] Morrison, C.J. (1997) “Assessing the Productivity of Information Technology Equipment in U.S.Manufacturing Industries”, *Review of Economics and Statistics*, Vol. LXXIX, No. 3, pp. 471–481.

[39] Murphy, K.M., A. Schleifer, & R. W. Vishny (1991) ”The Allocation of Talent: Implications for Growth”, *Quarterly Journal of Economics*, Vol. CVI, pp. 503-530.

[40] Parks, R.W. (1967) ”Efficient Estimation of a System of Regression Equations when Disturbances are Both Serially and Contemporaneously Correlated”, *Journal of the American Statistical Association*, Vol. 62, pp. 500-509.

[41] Oliner, S.D. & D. E. Sichel (2000) ”The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?”, *Journal of Economic Perspectives*, Vol. 14, pp. 3-22.

[42] Parsons, D., C.C. Gotlieb, & M. Denny (1993) ”Productivity and Computers in Canadian Banking”,*Journal of Productivity Analysis*, Vol. 4 pp. 95–113.

[43] Pesaran, M. H. & A.D. Hall (1998) ”Tests of Non-Nested Linear Regression Models Subject to Linear Restrictions”, *Economics Letters*, Vol. 27, pp. 341-348.

[44] Romer, P.M. (1990) ”Endogenous Technical Change”, *Journal of Political Economy,* Vol. 98, pp. S71-S102.

[45] Siegel, D. (1997) ”The Impact of Computers on Manufacturing Productivity Growth: A Multiple–Indicators, Multiple–Cause Approach”, *Review of Economics and Statistics*, Vol. LXXIX, No. 1, pp. 69–78.

[46] Solow, R.L. (1956) ”A Contribution to the Theory of Growth”, *Quarterly Journal of Economics,* Vol. LXX, pp. 65–94.

[47] Solow, R.L. (1987) ”We'd Better Watch Out”, *New York Times Book Review,* July 12, p. 36.

[48] Stiroh, K.J. (2002) ”Information Technology and the US Productivity Revival: What Do the Industry Data Say?”, American Economic Review, Vol. 92, pp. 1559-1576.

[49] Triplett, J.E. (1999) ”The Solow Productivity Paradox: What Do Computers Do to Productivity?”, *Canadian Journal of Economics*, Vol. 32, pp. 309–334.

[50] Weinberg, B.A. (2000) ”Computer Use and the Demand for Female Workers”, *Industrial and Labor Relations Review*, Vol. 53, pp. 290–308.

A Computation of omputer capital

The Swedish National Accounts (SNA) provides data on capital stocks of equipment and structures (buildings) by 2- or 3-digit industries. In this section we show how the equipment capital stock can be decomposed into two parts, one computer capital stock and one stock för non-computer equipment. To this end, we first have to to consider the computation of the SNA capital stocks and and the corresponding capital rental prices.

To simplify the notation, we here suppress industry indices and denote the equipment stocks by $K_{E,t}$ and the stocks of structures by $K_{B,t}$.The stocks are defined such that the period t stock denotes the stock as of January 1, year t.

The perpetual inventory method used in the SNA to compute the stocks implies that they can be closely approximated by the following accumulation formula

$$K_{i,t} = \left(1 - \overline{\delta}_i\right) K_{i,t-1} + I_{i,t-1}, \qquad i = E, B. \tag{29}$$

The capital rental prices for equipment and structure capital are constructed according to

$$P_{K_i,t} = P_{I_i,t-1}\left[r_{t-1} + \overline{\delta}_i \frac{\left(P_{I_i,t|t-1}\right)^e}{P_{I_i,t-1}} - \left(\frac{\left(P_{I_i,t|t-1}\right)^e - P_{I_i,t-1}}{P_{I_i,t-1}}\right)\right] \tag{30}$$

where $P_{K_i,t}$ denotes the rental price for type i captal at the beginning of period t, $P_{I_i,t-1}$ is the gross investment price index for type i capital and period $t-1$, r_{t-1} is a long-term interest rate measured at the very end of period $t-1$, and $\left(P_{I_i,t|t-1}\right)^e$ is the expected value of the investment price index for type i capital in period t, given information about this index up to (and including) period $t-1$. The difference $\left(P_{I_i,t|t-1}\right)^e - P_{I_i,t-1}$ measures the expected windfall profit (loss) that accrues to the owner of the capital asset through an increase (decrease) in the renewal cost.[35]

Like the $\overline{\delta}_i$, the P_{I_i} are obtained from the SNA. The interest rate r is measured by means of the nominal rate on Swedish long-term industrial bonds. The expectional variable $\left(P_{I_i,t|t-1}\right)^e$ is implemented by means of

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[35] The rental price formula (30) corresponds to the one given by equation (B4) in Jorgenson & Stiroh (2000). The only difference being that Jorgenson and Stiroh (op.cit.) assume perfect foresight with respect to the investment price index, thus substituting $P_{I_i,t}$ for $\left(P_{I_i,t|t-1}\right)^e$.

a univariate Kalman filter.[36]
The rental prices are normalized to unity in a base-year t_o – here set to 1991 – yielding:

$$\widetilde{P}_{K_i,t} = \frac{P_{K_i,t}}{P_{K_i,t_o}}. \tag{31}$$

To preserve the property that price × quantity = cost, the quantity of capital is normalized accordingly, i.e.

$$\widetilde{K}_{i,t} = P_{K_i,t_o} K_{i,t} \tag{32}$$

such that $\widetilde{P}_{K_i,t}\widetilde{K}_{i,t} = P_{K_i,t}K_{i,t}$.

To obtain the computer capital stock, we split the equipment stock K_E into K_{E_C} and K_{E_M} where subindex C denotes Computers and subindex M stands for machines (that are not computers). In analogy with (29):

$$K_{E_C,t} = (1 - \delta_{E_C}) K_{E_C,t-1} + I_{E_C,t-1} \tag{33}$$

To make (33) operational, we have to decide on a value for δ_{E_C} and on an initial value for K_{E_C}.

We have set $\delta_{E_C} = \frac{1}{3}$. One motivation is that in the SNA depreciation rates for equipment (including computers) varies between 0.16 and 0.21. As computer capital depreciates much faster than other types of equipment δ_{E_C} should considerably larger than 0.21, making $\frac{1}{3}$ a rather reasonable number. It is also close to the depreciation rate of 0.315 (from the Bureau of Economic Analysis) employed by Jorgenson & Stiroh (op.cit.).

The initial value for K_{E_C} is obtained by extrapolating gross investments, I_{E_C}, backwards. To this end, we have assumed that investments during the period 1980-1994 can be approximated by the arithmetic average of the 1985 and 1986 gross investments.

For the computation of the TFP growth rate according to Section 5.1, we also need a capital rental price for computer capital. The computation of this rental price is very similar to (30). For the gross investment price index $P_{I_{E_C},t}$ we use an import price for computers and peripherals, normalized to unity in 1991. Unfortunately, this index can only be computed for 1984-1995. During this period the index shows a continous decrease

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[36] This filter amounts to modeling the price index by means of a transition equation and a measurement equation. The former models the "true" investment price index as a random walk, incorporating a drift in the form of a deterministic quadratic time trend. The measurement equation models the observed price index as the sum of the "true" index and a random error.

in the price of computers and peripherals, at an increasing rate. Between 1984 and 1985 the rate of decrease was very small, only 0.1 %, while between 1994 and 1995 the index fell by 14.3 %. The arithmetic mean of the rates of price decreases over the period was around 6.5 %.[37]
As our time series on $P_{I_{E_C},t}$ is so short we cannot model the expected investment price index by means of a Kalman filter. Instead we have simply fitted a linear trend to the log-differences of the index, to estimate the average rate of decrease in the yearly price reductions, i.e. the discrete analogue of the second order derivative. We obtain an estimate of -1.24 percent annually, implying that for computer capital the last term within brackets in (30).is equal to zero in 1985 and the falls cumulatively by -1.24 each year, to reach -12.4 percent in 1995.

Given the stock of computer capital and the computer capital rental price we can consistently solve for the expenditures on (non-computer) machinery equipment. Denoting these expenditures by $V_{K_{E_M},t}$ we get

$$V_{K_{E_M},t}\left(\equiv \widetilde{P}_{K_{E_M},t}\widetilde{K}_{K_{E_M},t}\right) = \widetilde{P}_{K_E,t}\widetilde{K}_{E,t} - \widetilde{P}_{K_{E_C},t}\widetilde{K}_{E_C,t} \tag{34}$$

because rental expenditures on computers and non-computer machinery have to add up to total rental expenditures on equipment capital.

The final step is determine $\widetilde{P}_{K_{E_M},t}$ and $\widetilde{K}_{K_{E_M},t}$. To solve for $\widetilde{P}_{K_{E_M},t}$, we first assume that the rental price of equipment capital can be approximated by a translog aggregate of $\widetilde{P}_{K_E,t}$ and $\widetilde{P}_{K_E,t}$:

$$\begin{aligned}\Delta \ln \widetilde{P}_{K_E,t} &= \tfrac{1}{2}\left(S_{t-1}+S_t\right)\cdot\Delta\ln\widetilde{P}_{K_{E_C},t} \\ &\quad + \tfrac{1}{2}\left[(1-S_{t-1})+(1-S_t)\right]\cdot\Delta\ln\widetilde{P}_{K_{E_M},t}\end{aligned} \tag{35}$$

where

$$S_t = \frac{\widetilde{P}_{K_{E_C},t}\widetilde{K}_{E_C,t}}{\widetilde{P}_{K_{E_C},t}\widetilde{K}_{E_C,t} + V_{K_{E_M},t}}. \tag{36}$$

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[37] This may seem like a rather small rate of price decrease. It is smaller than similar estimates for the US but the difference is not as large as one might think. For comparison, Jorgenson and Stiroh (2000) report an average rate of decrease in the price of computer investments equal to 12.8 percent over the period 1985-1995. For communications investment they find a much smaller rate of decrease, namely 0.6 percent over the same period. Thus, the decline in prices differs substanntially between different types of computerrelated equipment. In our case, it might be that the prices of peripherals have fallen not fallan as fast as the prices of computers. Unfortunately, we cannot check this conjecture, as there is no separate price index for computers.

Solving for $\Delta \ln \widetilde{P}_{K_{E_M},t}$, we obtain

$$\begin{aligned} \Delta \ln \widetilde{P}_{K_{E_M},t} \quad = \quad & \frac{1}{\frac{1}{2}[(1-S_{t-1})+(1-S_t)]} \cdot \Delta \ln \widetilde{P}_{K_E,t} \\ & - \frac{\frac{1}{2}(S_{t-1}+S_t)}{\frac{1}{2}[(1-S_{t-1})+(1-S_t)]} \cdot \Delta \ln \widetilde{P}_{K_{E_C},t} \, . \end{aligned} \tag{37}$$

The equation (37) determines the rate of change in $\widetilde{P}_{K_{E_M},t}$ but not its level. However, the level is determined by the normalization that $\widetilde{P}_{K_{E_M},t}$, just like $\widetilde{P}_{K_E,t}$ and $\widetilde{P}_{K_{E_C},t}$, should be equal to unity in the base-year. Thus,

$$\widetilde{P}_{K_{E_M},t_o} \equiv 1.0 \, . \tag{38}$$

Given $\widetilde{P}_{K_{E_M},t}$ we can finally solve for $\widetilde{K}_{K_{E_M},t}$ according to

$$\widetilde{K}_{K_{E_M},t} = \frac{V_{K_{E_M},t}}{\widetilde{P}_{K_{E_M},t}}, \tag{39}$$

which constitutes the final step in the break-down of the equipment capital stock into computer capital and (non-computer) machinery capital.

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