ECONOMIC RESEARCH REPORTS

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RR# 98-07 **February 1998**

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Taxation, Investment, and Firm Growth with Heterogeneous Capital

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First Draft: November 7, 1997

Abstract

Capital heterogeneity has largely been ignored in studies of investment behavior. We estimate a dynamic structural model in which different types of capital are interrelated in both the production and adjustment cost technologies. Our results help explain some of the empirical failings of the neoclassical model. We show that when capital heterogeneity is ignored estimates of adjustment costs are biased upward, and estimates of factor substitution in production are biased downward. Our second principle result is that investment is not positively correlated with changes in internal net worth — as measured by cash flow — except when capital heterogeneity is restricted. Hence cash flow may matter in other studies not because it parameterizes a liquidity constraint, but because it is correlated with features of the technology that are ignored by assuming that capital is homogeneous. Our estimates suggest that different types of capital are significantly greater than unit elastic substitutes in production and complements in adjustment. We study the steady state and dynamic implications of these findings. In the steady state analysis, we highlight that in a model with multiple capital goods seemingly identical changes in the cost of capital lead to different investment responses. Regardless of the steady state effect of policy, in the dynamic analysis, investment in different types of capital will tend to be coordinated. Our simulations show that this complementarity in the technology of investment is an economically important magnification and propagation mechanism.

JEL Classification: D24, E22, E23
Keywords: Production; Investment; Multiple Capital Goods

We thank Rosanne Altshuler, Ned Nadiri, and Wilbert Van Der Klaauw for helpful comments and suggestions. Cummins gratefully acknowledges financial support from the C. V. Starr Center for Applied Economics.

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1 Introduction

Capital is heterogeneous. Afterall, a printer is not a pipeline. But in empirical studies of the neoclassical model of investment capital heterogeneity has largely been ignored. The implicitly maintained assumption in most studies is that the technological relationship between neoclassical fundamentals and investment is the same regardless of whether there are many types of capital goods or a single type. However, heterogeneous types of capital can be aggregated into a single capital aggregate in a dynamic model only in very restrictive circumstances (Blackorby and Schworm 1983; Epstein 1983; Wildasin 1984). A particularly stringent requirement is that the capital goods must be weakly separable. Then the capital aggregate can be expressed as a weighted sum of the different types of capital goods. However, this assumption is unappealing since it means that different capital goods are perfect substitutes — i.e., for the purposes of producing output, a printer is a pipeline and the converse. Moreover, the problem is exacerbated by aggregating over firms. In this case, the rates of substitution in production between different types of capital must be the same for every firm.

While data limitations have prevented an exhaustive categorization of how capital goods are related at different data frequencies and levels of aggregation, there are many studies that reject the hypothesis that different types of capital goods are perfect substitutes. For example, Denny and May (1978) find that the elasticities of substitution between equipment and other factors of production are significantly different from the elasticities between structures and other factors. Since direct evidence suggests that capital goods cannot be aggregated consistently, the estimates of the technological parameters in virtually every study of investment may vary, perhaps in economically important ways, from the true ones. Based on this insight, we highlight two primary sources of concern with the single capital good model.

The first concern is that the assumption of a single capital good is responsible for why the neoclassical model has performed poorly in numerous empirical studies (for a survey, see Chirinko 1993a). We focus on whether some of the deficiencies are alleviated in a model with multiple capital goods. In particular, we examine whether a multiple capital goods model yields more reasonable estimates of the marginal adjustment costs of investment than those usually estimated. In addition, we investigate whether there is evidence of capital market imperfections in our richer model by studying how changes in internal funds affect investment.

The second concern is that the single capital good model inadequately describes the effects of tax policy and demand and supply shocks by ignoring changes in the composition of investment. The prices of capital goods vary widely across assets and over time. These price swings have different effects on investment incentives. Two examples illustrate the magnitude of these differences. First, the price of producers' durable equipment relative to nonresidential structures has fallen monotonically from 1.48 in 1970 to 0.86 in 1995 (a 42 percent decrease). Second, in our dataset, the Tax Reform Act of 1986 (TRA86) — which eliminated the investment tax credit (ITC), reduced the generous depreciation allowances allowed for most types of PDE, and cut the corporate income tax — increased the after-tax price of equipment relative to structures from 0.73 in 1985 to 0.81 in 1987 (an 11 percent increase).[1] In a single capital good model the effects of these types of changes must be ignored.

In our model we address these concerns by introducing heterogeneous capital goods into the production and adjustment cost technologies. We estimate the parameters of these technologies from a system of interrelated equations for the production and capital demand functions. We estimate both "own" production and adjustment cost parameters and "cross" ones resulting from interrelated technologies. The "cross" effects in the production technology determine the degree of substitutability between factors of production. The "cross" effect in the adjustment cost technology indicates how adjustment costs are related. If the "cross" term is negative, the marginal adjustment costs of one type of investment are decreased by investment in another type. This decrease could reflect the fact that certain technologies are naturally complementary or that installation and training costs are smaller when investments are coordinated. More generally, it may be cheaper to adopt together rather than separately because of positive spillovers between different types of investment, resulting from, for example, the benefits of shared information. In contrast, a positive "cross" term may result from

[1] Epstein (1983) shows that Hick's Aggregation Theorem provides a basis for aggregating different capital goods into a single capital aggregate in a dynamic model. The proof requires that the rental prices of capital always be proportional. The above two examples suggest that this condition is not satisfied and a formal test confirms this intuition. In our dataset, the regression of the log of the equipment cost of capital (equation (12)) on the log of the structures cost of capital yields a slope coefficient estimate that is negative and statistically significant from unity.

additional costs of reorganizing and coordinating production across operations while integrating different types of new capital, or, more generally, from negative spillovers within the firm.[2]

The ideal dataset for estimation of our model would contain all the quantities and after-tax prices of the factors of production used at the firm or plant level. Unfortunately, such rich data do not exist. As a practical alternative, we use panel data on US firms that separates capital goods and investment by broad asset type. Since our measures are not completely disaggregated, our estimates also suffer from aggregation bias. Nevertheless, our results suggest that the empirical performance of our richer, albeit imperfect, specification helps to explain some of the failings of the neoclassical model.

Our estimated marginal adjustment costs are modest in magnitude and less than half of those estimated from a model in which adjustment costs are assumed to be unrelated. This results from the negative and statistically significant estimate of the "cross" adjustment cost parameter. According to our estimates, growth in one type of capital leads to an acceleration in the growth of the other type of capital. We also show that interrelated adjustment costs are important for understanding the substitution possibilities in the production technology. When interrelated adjustment costs are omitted, we find that production function parameter estimates are biased in favor of finding increasing returns and greater complementarity between factor inputs.

Our second main empirical result is that investment is not positively correlated with changes in internal net worth, as measured by cash flow. Evidence of liquidity constraints only appears when we restrict the production and adjustment cost functions to be unrelated (i.e., Cobb-Douglas production and separable adjustment cost functions). Since studies that purport to find liquidity constraints on investment employ

[2]Interrelated production technologies are standard (e.g., the CES or Translog). However, the types of technologies we are trying to model with interrelated adjustment costs may be less familiar. Milgrom and Roberts (1990) provide an example of adjustment cost complements (p. 514, italics added):

> Let us trace some of the indirect effects of a fall in the cost of computer-aided design (CAD) equipment and software that leads to the equipment being purchased. Some CAD programs prepare actual coded instructions that can be used by programmable manufacturing equipment, so one effect of the adoption of CAD may be to *reduce the cost of adopting* and using programmable manufacturing equipment. Since the prices of that equipment are also falling, the effects of the two prices changes on the adoption of that equipment are *mutually reinforcing*.

these restrictions, it suggests that cash flow may matter not because it parameterizes a liquidity constraint but because it is correlated with omitted parts of the marginal products of capital and the marginal costs of investment. Recently, Cummins, Hassett, and Oliner (1997) have found similar results using a different empirical investment equation.

We address the second concern by using our parameter estimates to simulate the effects of various changes in the economic environment. Our estimates suggest that different types of capital are greater than unit elastic substitutes. This means that changes in the fundamentals that affect the net return to investment in one type of capital strongly affect the demand for other types of capital. We emphasize that tax policy can have especially significant reallocative effects. For example, relative to a Cobb-Douglas baseline, the estimated parameters from our richer model imply that a re-introduction of the ITC on equipment will result in a 5 percentage point greater increase in the steady state equipment capital stock and a 3 percentage point greater increase in the structures capital stock.

Our simulations of the firms' growth rates show that the dynamic response to tax changes is different from what might be expected from a steady state analysis alone. For example, when the ITC is increased and adjustment costs are interrelated, total investment and structures investment are greater than when adjustment costs are unrelated. This dynamic result is due to the complementarity of equipment and structures in the adjustment cost technology. In general, this complementarity means that investments will co-vary positively regardless of the steady state effect of policy.

There are two previous studies in the investment literature that estimate multiple capital goods models. Hayashi and Inoue (1991) relate the growth rate of a scalar index of multiple capital inputs, in contrast to the sum of nominal investments usually used, and Tobin's Q. Their derivation relies on the assumption that capital inputs are weakly separable in the profit function. As discussed above, the drawback of this restriction is that it amounts to assuming that the capital goods are perfect substitutes.[3]

[3]Rather than test whether the hypothesis of weak separability can be rejected in their data, Hayashi and Inoue (1991) simply assume that it cannot be and appeal to the theoretical model in Epstein (1983) as justification. They claim that their specification, "considered previously by Epstein (1983), is a natural extension of the [single good adjustment cost model]." However, Epstein (1983) claims quite the opposite: "While in theory [weak separability] provides a basis for aggregation, it is argued that this method does not

Following Wildasin's (1984) suggestion, Chirinko (1993b) estimates an investment equation relating Tobin's Q to different types of investment. In this empirical framework there are many different investment equations that can be estimated.[4] While all of the equations are mathematically identical, Chirinko (1993b) finds that the choice of normalization affects the parameter estimates, even though the regression results should yield the same estimates. This suggests the model is misspecified and the only way to identify the adjustment cost parameters would be to model the misspecification (as, e.g., measurement error or omitted variables bias). Instead, Chirinko (1993b) restricts the adjustment cost parameters on different capital goods to be equal. Since the adjustment cost functions are assumed to be linear quadratic, this amounts to assuming that there is only a single capital good.

Our approach is more closely related to that taken in the numerous studies of dynamic factor demand. The studies in this literature characterize the firm's technology very generally but usually use aggregate time-series data for estimation (see, e.g., Pindyck and Rotemberg 1983a, 1983b).[5] Following the seminal contribution of Nadiri and Rosen (1969), some of the studies in this literature also formulate their models with interrelated adjustment costs (Epstein and Yatchew 1985; Shapiro 1986; Holly and Smith 1989). However, the technological connection between adjustment costs for different types of capital is most natural at the firm- or plant-level (see the example in footnote 2), and yet, to our knowledge, there are no studies that estimate dynamic factor demand models with interrelated adjustment costs using firm-level panel data.[6]

The paper is organized as follows. Section 2 introduces our theoretical model. Section 3 discusses the dataset and presents some stylized facts. Section 4 presents our estimation strategy and results. Section 5 describes our simulation results and the final section concludes.

provide a satisfactory basis for aggregation in practical situations. Thus the use of index numbers would seem to be inappropriate for the construction of aggregates of quasi-fixed factors."

[4]The number of different specifications is equal to $(n + 1)$, where n is the number of capital goods.

[5]In fact, most of the studies use a variant of a single time-series dataset developed by Berndt and Wood (1975).

[6]There are studies that use industry data (Bernstein and Nadiri 1989; Prucha and Nadiri 1996; Rossana 1990).

2 Model

Our model is a partial equilibrium optimal control problem based on the one Altshuler and Cummins (1997) introduced to study the demand for domestic and foreign capital by multinational corporations. To simplify the presentation we introduce the stochastic specification and functional forms of the model in section 4 where we discuss estimation.

We first define the firm's production and adjustment cost technologies.[7] There is a vector of quasi-fixed factors of production consisting of the beginning-of-period capital goods, $\mathbf{K}_{t-1} = \{K_{j,t-1}\}_{j=1}^{n}$, where j indexes the n goods, and t indexes time. The variable factor of production is V_t. The firm produces output, Y, using a quasi-concave production function:

$$Y_t = F(\mathbf{K}_{t-1}, V_t, m, t | \boldsymbol{\phi}), \tag{1}$$

where m is the industry index, introduced as an argument to account for differences in disembodied technical change across industries; similarly t is introduced to account for disembodied technical change over time; and $\boldsymbol{\phi}$ is a parameter vector describing the technical coefficients of production.

We assume that investment is subject to convex adjustment costs on net investment, $C(\mathbf{I}_t, \mathbf{K}_{t-1}, \boldsymbol{\delta} | \boldsymbol{\alpha})$, where $\mathbf{I}_t = \{I_{jt}\}_{j=1}^{n}$ is a vector of gross investments; $\boldsymbol{\delta} = \{\delta_j\}_{j=1}^{n}$ is a vector of constant geometric rates of economic depreciation; and $\boldsymbol{\alpha}$ is a parameter vector describing the technical coefficients of adjusting the capital stock.[8]

The after-tax net revenue, Π, is composed of gross revenues less adjustment costs and factor payments:

$$\begin{aligned}\Pi_t = \;& (1-\tau_t)[F(\mathbf{K}_{t-1}, V_t, m, t|\boldsymbol{\phi}) - C(\mathbf{I}_t, \mathbf{K}_{t-1}, \boldsymbol{\delta}|\boldsymbol{\alpha}) - v_t V_t] \\ & - \sum_{j=1}^{n} \left[(1-k_{jt}) p_{jt} I_{jt} + \tau_t \int_{-\infty}^{t} p_{ju} I_{ju} D_j(t, t-u) du \right],\end{aligned} \tag{2}$$

[7] The firm index i is suppressed to economize on notation except where essential.

[8] We assume that the adjustment costs are internal to the firm and take the form of foregone output. Models incorporating internal adjustment costs have been developed by Eisner and Strotz (1963); Treadway (1971); Mortensen (1973); Epstein (1981).

where τ is the statutory corporate income tax rate; k_j is the investment tax credit for capital good j; $D_j(t, t-u)$ is the depreciation allowance per dollar of date u expenditure on capital good j; and v and p are the prices the variable input and investment goods relative to output, respectively.[9]

The present discounted value of future profits is:

$$P_t = \int_t^{\infty} e^{-r(s-t)} \Pi_s \eta_s ds, \tag{3}$$

where r is the nominal after-tax required rate of return on capital; and η is the tax discrimination parameter that determines the relative tax advantage of dividends against retained earnings. Under the US tax system, $\eta_s = (1 - m_s)/(1 - z_s)$, where m is the personal tax rate on dividends and z is the accrual-equivalent capital gains tax rate.

We substitute equations (1) and (2) into equation (3) to yield:

$$\begin{aligned} P_t = & \int_t^{\infty} e^{-r(s-t)} \eta_s \Big\{ (1 - \tau_s) \Big[F(\mathbf{K}_{s-1}, V_s, m, t | \boldsymbol{\phi}) - C(\mathbf{I}_s, \mathbf{K}_{s-1}, \boldsymbol{\delta} | \boldsymbol{\alpha}) - v_s V_s \Big] \\ & - \sum_{j=1}^{n} \Big[p_{js} I_{js} \Gamma_{js} - B_{js} \Big] \Big\} ds, \end{aligned} \tag{4}$$

where Γ_{js} is one minus the present discounted value of the net tax benefit of one dollar of date s investment in capital good j: $\Gamma_{js} = 1 - k_{js} - \int_s^{\infty} e^{-r(u-s)} \tau_{ju} D_j(u, u - s) du$. The term B_{js} summarizes the value of depreciation allowances on investments predetermined at date s: $B_{js} = \tau_{js} \int_{-\infty}^{s} p_{ju} I_{ju} D_j(s, s - u) du$.

The firm chooses the levels of its factor inputs at time t to maximize equation (4) subject to the capital stock accounting identities:

$$I_{jt} = \dot{K}_j + \delta_j K_{j,t-1}. \tag{5}$$

Although we have ignored financing issues by assuming that the firm finances investment out of retained earnings, we can introduce these considerations in a simple way

[9]Notice that we have assumed that the adjustment cost function is additively separable from the production function. This is a standard assumption in the empirical literature because it makes the estimation problem tractable (see, e.g., Lichtenberg 1988). However, additive separability has important implications for the dynamics of the problem. In particular, Scheinkman (1978) shows that this assumption assures that the firm's capital stock vector converges to a unique stationary point which is independent of initial conditions. This result should be kept in mind while interpreting the simulation results in section 5 since it rules out optimal trajectories that are closed limit cycles as in, e.g., Benhabib and Nishimura (1979).

by constraining net revenue to be non-negative, $\Pi_t \geq 0$.[10] Associating the multipliers λ_j with equation (5), and μ with the constraint $\Pi_t \geq 0$, the maximization yields the following first-order conditions:

$$(\eta_t + \mu_t)(F_{V_t} - v_t) = 0 \qquad \forall t; \tag{6}$$

$$\lambda_{jt} - (\eta_t + \mu_t)[(1 - \tau_t)C_{I_{jt}} + p_{jt}\Gamma_{jt}] = 0 \qquad \forall j, t; \tag{7}$$

$$\Pi_t \geq 0, \; \Pi_t \mu_t = 0 \qquad \forall t. \tag{8}$$

Marginal q is defined as the ratio of the marginal after-tax cost of investment, including adjustment costs, to its market price:

$$q_{jt} = \frac{\lambda_{jt}}{p_{jt}} = \frac{(\eta_t + \mu_t)[(1 - \tau_t)C_{I_{jt}} + p_{jt}\Gamma_{jt}]}{p_{jt}}. \tag{9}$$

Notice that since adjustment costs are on net investment, steady state marginal adjustment costs are zero and therefore $q_j = (\eta + \mu)\Gamma_j$.

The Euler equations for the optimal path of capital stocks are:

$$(\eta + \mu)(1 - \tau)\Pi_{K_j} = p_j q_j \left(r + \delta_j - \frac{\dot{q}_j}{q_j} - \frac{\dot{p}_j}{p_j} \right). \tag{10}$$

This equation equates the after-tax marginal product of capital net of adjustment costs (LHS) to the marginal cost of capital (RHS).[11]

In the steady state this equation is the familiar cost of capital which we denote as c_j:

$$\Pi_{K_j} = c_j = \frac{p_j(r + \delta_j)\Gamma_j}{(1 - \tau)}. \tag{11}$$

[10] A number of studies use this basic strategy to incorporate capital market imperfections (see, e.g., Himmelberg 1990; Hubbard and Kashyap 1992; Hubbard, Kashyap, and Whited 1995). While these studies provide the firm with a richer menu of financing alternatives than in this model, our empirical approach for testing for liquidity constraints will be directly comparable.

[11] We rule out explosive equilibria by assuming that the following transversality conditions on capital hold: $\lim_{t \to \infty} e^{-rt} q_{jt} K_{jt} = 0 \; \forall j$.

Equations (9), (10), (11) are the basis for nearly all empirical studies of investment. In the single capital good model, equation (9) can be inverted to obtain an estimable relationship between the investment-capital ratio and Tobin's average Q.[12] In our model this approach is generally infeasible since there is no closed form solution for the investment-capital ratios (except in the special case when $C_{I_i I_j} = 0$, or equivalently $\alpha_{ij} = 0$).[13]

Another approach is to approximate the optimal solution for small perturbations by linearizing equation (10) around the steady state. By imposing some structure on the production and adjustment cost technologies, this approach gives explicit analytical expressions that summarize the effect of the cost of capital on investment. These expressions can then be used as regression equations (Auerbach and Hassett 1992). Unfortunately, as Auerbach (1989) points out, a model with multiple interrelated capital stocks is too complicated to analyze in this framework.[14] In addition, a potential problem with this approach is that the approximation error involved in linearizing a complicated model may be significant (Judd and Guu 1997).

We adopt an alternative approach from the dynamic factor demand literature (for citations see the Introduction). We use firm-level panel data to estimate the structural

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[12]Letting $n = 1$ and $C_I = \alpha(\frac{I_t}{K_{t-1}} - \delta)$, equation (9) can be rearranged to express the investment-capital ratio in terms of tax-adjusted marginal q:

$$\frac{I_t}{K_{t-1}} = \delta + \frac{1}{\alpha}\frac{p_t[q_t - (\eta_t + \mu_t)\Gamma_t]}{(\eta_t + \mu_t)(1 - \tau_t)}.$$

Provided the net revenue and adjustment cost functions are linear homogeneous, and the firm operates in perfectly competitive markets, Tobin's average Q — defined as the ratio of the market value of the firm to the replacement cost of its capital stock — can be substituted for marginal q to obtain an estimable investment equation (Hayashi 1982). It is interesting to note that in spite of the frequent use of this equation to test for the presence of liquidity constraints, it suffers from a serious defect. If $(\eta_t + \mu_t)$ is omitted from average Q, it is impossible to separately identify the adjustment cost parameter from the shadow value of internal finance. If $(\eta_t + \mu_t)$ is incorporated in average Q, the term cancels so that investment is unaffected by the non-negativity constraint on profits.

[13]Auerbach and Hines (1987) develop a model with adjustment costs on equipment, structures, and total investment. They interpret the elasticity of the equipment investment-capital ratio with respect to q as the inverse sum of the marginal adjustment costs associated with equipment and total investment, $(\alpha_{ee} + \alpha_{es})^{-1}$, where α_{ee} is their adjustment cost parameter on equipment and α_{es} is their "cross" adjustment cost parameter. A problem with this interpretation is that it requires the investment-capital ratios for equipment and structures to be equal, even in the steady state, which is infeasible since their depreciation rates differ.

[14]The complexity added by considering multiple capital stocks is also discussed in footnote 18 of Auerbach and Hassett (1992). In that study, equipment and structures investment equations are estimated separately, although the cost of capital for the other type of capital is entered as a regressor in each. While adding the other cost of capital may ameliorate some of the omitted variable bias, the difficulty with estimating only one type of capital demand is that the identification of the structural parameters requires that capital goods be weakly separable.

parameters of the production and adjustment cost technologies using equations (1) and (10). We then use the estimates to calibrate the simulation analysis in section 5. Before presenting our estimation procedure we briefly discuss our dataset and some key stylized facts.

3 Data

The dataset is a panel of firms from the 1996 Compustat industrial and full-coverage files. Compustat disaggregates capital into its two primary components, equipment and machinery, and structures.[15] While the ideal dataset would disaggregate capital completely, Compustat is a practical alternative since it is the only dataset we know of that reports disaggregated capital stocks at the firm level.

The 1996 Compustat file contains data from 1976 until 1995. In our estimation we use up to 4 lags of variables that contain beginning-of-period capital stocks so the first 5 years of the sample are excluded from estimation. We also exclude the last three years since there is a trade-off between the length of the panel and the number of firms in it. Thus there are no missing data during the estimation period (1981–1992). However, when lagged instrumental variables dated before 1981 are missing, the firm-year observation is dropped from estimation. As a result, in the sample used for estimation there are an average of 356 firms per year and 4317 firm-year observations.

A detailed description of how the dataset is constructed is contained in appendix A. In table 1 we provide the means, medians, and standard deviations of the primary variables in 1987 dollars for 1981 to 1992. The first four columns contain output and the factors of production. The sample statistics indicate that there is wide variation in the size of firms and the composition of their capital stocks. The means and medians of variable input are between 80 and 90 percent of the means and medians of output.[16]

[15] The stocks of natural resources, land, and leases are also reported but are missing so frequently that they are not useful for empirical work. In future research we plan to include research and development as a factor of production as well since it is often reported.

[16] Labor expense is included in variable input since it is not reported frequently enough to include it as a separate variable factor of production. There is substantial evidence that labor adjustment costs are negligible in US data at the annual frequency, justifying our specification of it as a variable factor (see, Hammermesh 1993).

The means and medians of the equipment (structures) capital stock are about 10 to 20 (5 to 10) percent of the means and medians of output.

The fifth and sixth columns contain the ratios of gross equipment and structures investment to their beginning-of-period capital stocks. Both the mean and median of the equipment investment-capital ratio are usually greater than 0.20. The mean and median of the structures investment-capital ratio are typically between one-half and one-third as large.

The final two columns present the costs of capital for equipment and structures. These user costs are calculated from equation (10) assuming weak separability of equipment and structures and no adjustment costs:

$$\widehat{\Pi}_{K_{jt}} = \widehat{c_{jt}} = \frac{p_{jt}\Gamma_{jt}\left[\rho_{jt} + \delta_j - \left(\frac{\Delta\Gamma_{j,t+1}}{\Gamma_{jt}}\right)\right]}{(1-\tau_t)}, \tag{12}$$

where $\rho_{jt} = r_t - \frac{\Delta p_{j,t+1}}{p_{jt}}$. In spite of the more generous tax incentives granted to equipment investment, the equipment cost of capital is always greater than the structures cost of capital because equipment depreciates much more quickly. Over time two trends dominate the changes in the relative costs of capital. The price of equipment has fallen relative to the price of structures and the generous tax incentives granted to equipment (in the form of the ITC and accelerated depreciation) were largely eliminated by TRA86.

There are two key stylized facts about equipment and structures in the firm data. First, there appears to be substantial substitutability between the factors of production. Figures 1 and 2 summarize the degree of substitution possibilities. The left panel of figure 1 plots the equipment and structures shares of output from 1977 to 1994. Both are increasing, and the equipment share is more variable. The right panel plots the variable input share. There is no discernable long term trend, and the variation is counter-cyclical. Figure 2 shows the relative factor shares. The left panel contains the equipment share relative to the structures share. The ratio is increasing in the earlier and later years, but drops sharply in the mid-1980s, reflecting the increase in the relative price of equipment caused by TRA86. The middle panel contains the equipment share relative to the variable input share. The ratio tends to increase over the entire period. Finally, the right panel contains the structures share relative to the variable input share. This ratio also tends to increase over the entire period.

The second stylized fact is that although the data suggest that there are substitution possibilities between equipment and structures capital, equipment and structures investment appear to be complements. Figure 3 illustrates the comovement in four ways. The ratios of equipment and structures gross (net) investment to total capital are plotted in the northwest (northeast) quadrant. The series move together closely. Similarly, net investments as a share of output (southwest quadrant) or value added (southeast quadrant) co-vary positively.

The structural estimation in the following section captures these two stylized facts formally, but this first look at the data explains why we find that factors are substitutes and investments are complements.

4 Estimation and Empirical Results

4.1 Estimation Methodology

To estimate the structural parameters of the model, we rewrite the Euler equations for firm i (equation (10)) in discrete time and introduce uncertainty:

$$\mathrm{E}_t\left\{\beta_{i,t+1}(\eta_{t+1}+\mu_{i,t+1})\left[\frac{\partial\Pi_{ij,t+1}}{\partial K_{ij,t+1}}-(1-\delta_j)\frac{\partial\Pi_{ij,t+1}}{\partial I_{ij,t+1}}\right]\right\}=-(\eta_t+\mu_{it})\left(\frac{\partial\Pi_{ijt}}{\partial I_{ijt}}\right), \quad (13)$$

where $\beta_{i,t+1}=(1+\rho_{i,t+1})^{-1}$.

We impose rational expectations to eliminate the expectations operator in equation (13). This allows us to substitute observed values of the variables for their expectations. We allow for expectational errors, $\epsilon_{ij,t+1}$, that are the sum of three components:

$$\epsilon_{ij,t+1}=u_i+\upsilon_{j,t+1}+\omega_{ij,t+1} \qquad \text{where} \quad \mathrm{E}_t(\epsilon_{ij,t+1})=0, \quad \mathrm{E}_t(\epsilon^2_{ij,t+1})=\sigma^2_{\epsilon_j}. \quad (14)$$

The first error component, u_i, is a firm-specific effect accounting for unobserved heterogeneity. The second error component, $\upsilon_{j,t+1}$, is a time-specific effect capturing macroeconomic shocks to each investment decision. Finally, the third error component, $\omega_{ij,t+1}$, is a stochastic disturbance that represents idiosyncratic optimization errors in each investment decision.[17]

We assume the firm's production technology, equation (1), can be approximated by a translog function:

$$y_{it} = \phi_0 + \sum_{k=1}^{K} \phi_k x_{kt} + \frac{1}{2} \sum_{k=1}^{K} \sum_{l=1}^{K} \phi_{ik} x_{ikt} x_{ilt} + \sum_{t=1}^{T-1} \phi_t D_t + \sum_{m=1}^{M-1} \phi_m D_m + \varepsilon_{it}, \tag{15}$$

where lowercase letters represent the logarithms of variables; x_k are factor inputs; K is the total number of factors; D_t are year dummy variables that represent disembodied technical change over time; D_m are one-digit industry dummy variables that capture differences in disembodied technical change across industries; T and M are the total numbers of years and one-digit industries in the panel, respectively; and ε_{it} is a productivity shock realized after input decisions are made, $\mathrm{E}_t(\varepsilon_{it}) = 0$, $\mathrm{E}_t(\varepsilon_{it}^2) = \sigma_\varepsilon^2$.[18]

We chose the translog because it is a flexible functional form that provides a second-order approximation to any arbitrary continuous twice-differentiable production function and allows for non-unitary substitutability between inputs. Then the marginal products of equipment and structures capital in period $t+1$ are, respectively:

$$\begin{aligned} \frac{\partial F_{i,t+1}}{\partial K_{iet}} &= \frac{Y_{i,t+1}}{K_{iet}} \left(\phi_{K_e} + \phi_{K_e K_e} k_{iet} + \phi_{K_e K_s} k_{ist} + \phi_{K_e V} v_{i,t+1} \right); \\ \frac{\partial F_{i,t+1}}{\partial K_{ist}} &= \frac{Y_{i,t+1}}{K_{ist}} \left(\phi_{K_s} + \phi_{K_s K_s} k_{ist} + \phi_{K_e K_s} k_{iet} + \phi_{K_s V} v_{i,t+1} \right). \end{aligned} \tag{16}$$

[17]The stochastic specification of the Euler equations is based on expectations errors for expositional convenience. Alternatively, we could have incorporated the shocks in the production and adjustment cost technologies and derived a qualitatively identical specification — although the interpretation of the error components would differ (e.g., the idiosyncratic optimization errors would be relabeled as capital-biased productivity shocks realized after input decisions are made).

[18]Alternatively, we could assume that the productivity shock is observable to the firm but not to the econometrician. In this case, variable inputs, V_t, would be correlated with ε_t. In addition, if the shock is serially correlated and demand for fixed inputs is determined by expectations of future realizations of ε, then $\mathbf{K}_{t-1}$ would also be correlated with ε_t. The GMM estimator we present below is robust to this type of simultaneity bias when the Sargan test is not rejected. Mairesse and Hall (1996) take this approach to production function estimation as well, although their model is static.

We assume that adjustment costs take the following quadratic form in net investment and capital:[19]

$$\begin{aligned} C = \; & \tfrac{\alpha_{ee}}{2}\left(\tfrac{I_{iet}}{K_{ie,t-1}} - \delta_e\right)^2 K_{ie,t-1} + \tfrac{\alpha_{ss}}{2}\left(\tfrac{I_{is}}{K_{is,t-1}} - \delta_s\right)^2 K_{is,t-1} \\ & + \tfrac{\alpha_{es}}{2}\left[\left(\tfrac{I_{iet}}{K_{ie,t-1}} - \delta_e\right)\sqrt{K_{ie,t-1}} + \left(\tfrac{I_{ist}}{K_{is,t-1}} - \delta_s\right)\sqrt{K_{is,t-1}}\right]^2 . \end{aligned} \tag{17}$$

Then the marginal adjustment costs of equipment and structures investment are, respectively:

$$\begin{aligned} \frac{\partial C}{\partial I_{iet}} &= (\alpha_{ee} + \alpha_{es})\left(\frac{I_{iet}}{K_{ie,t-1}} - \delta_e\right) + \alpha_{es}\sqrt{\frac{K_{is,t-1}}{K_{ie,t-1}}}\left(\frac{I_{ist}}{K_{is,t-1}} - \delta_s\right); \\ \frac{\partial C}{\partial I_{ist}} &= (\alpha_{ss} + \alpha_{es})\left(\frac{I_{ist}}{K_{is,t-1}} - \delta_s\right) + \alpha_{es}\sqrt{\frac{K_{ie,t-1}}{K_{is,t-1}}}\left(\frac{I_{iet}}{K_{ie,t-1}} - \delta_e\right). \end{aligned} \tag{18}$$

This specification allows investment in one type of capital to affect the marginal adjustment cost of the other type.[20] If α_{es} is positive, increasing investment in one type of capital increases the marginal adjustment costs of the other type. This increase could result from a production process in which it is more costly to coordinate the integration and installation of many capital goods at once. If α_{es} is negative, increasing investment in one type of capital decreases the marginal adjustment cost of the other type. This decrease could result because certain technologies are naturally complementary (see the example in footnote 2), or, more generally, from positive spillovers within the firm that reflect, for example, the benefits of shared information.[21]

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[19] Alternatively we could postulate that adjustment costs are on gross investment by setting $\delta_j = 0$ in equation (17) (see, e.g., Gould 1968; Treadway 1969; Abel 1985; Pindyck 1982; for a recent survey of adjustment costs see, Hammermesh and Pfann 1996). We found that estimates of this model were rejected in favor of one with adjustment costs on net investment.

[20] To see this consider the derivative of the marginal adjustment cost of one type of investment with respect to the other type:

$$\frac{\partial^2 C}{\partial I_{iet}\partial I_{ist}} = \frac{\alpha_{es}}{\sqrt{K_{ie,t-1}K_{is,t-1}}}.$$

[21] To ensure convexity of the adjustment cost function we must restrict the domain of α_{es}. The condition for convexity is:

$$\alpha_{es} > -\frac{\alpha_{ee}\alpha_{ss}}{(\alpha_{ee} + \alpha_{ss})}.$$

Substituting expressions for $\frac{\partial \Pi_i}{\partial K_{ie}}$ and $\frac{\partial \Pi_i}{\partial I_{ie}}$ into equation (13) yields the following Euler equation for equipment:

$$\begin{aligned}
&\beta_{t+1}\left(\frac{\eta_{t+1}+\mu_{i,t+1}}{\eta_t+\mu_{it}}\right)\left(\frac{1-\tau_{t+1}}{1-\tau_t}\right)\Bigg\{\frac{Y_{i,t+1}}{K_{iet}}\left(\phi_{K_e}+\phi_{K_eK_e}k_{iet}+\phi_{K_eK_s}k_{ist}+\phi_{K_eV}v_{i,t+1}\right)\\
&+\frac{\alpha_{ee}}{2}\left(\frac{I_{ie,t+1}}{K_{iet}}-\delta_e\right)^2+\frac{\alpha_{es}}{2}\left[\left(\frac{I_{ie,t+1}}{K_{iet}}-\delta_e\right)^2+\sqrt{\frac{K_{ist}}{K_{iet}}}\left(\frac{I_{ie,t+1}}{K_{iet}}-\delta_e\right)\left(\frac{I_{is,t+1}}{K_{ist}}-\delta_s\right)\right]\\
&+(1-\delta_e)\left[(\alpha_{ee}+\alpha_{es})\left(\frac{I_{ie,t+1}}{K_{iet}}-\delta_e\right)+\alpha_{es}\sqrt{\frac{K_{ist}}{K_{iet}}}\left(\frac{I_{is,t+1}}{K_{ist}}-\delta_s\right)+p_{e,t+1}\left(\frac{\Gamma_{ie,t+1}}{1-\tau_{t+1}}\right)\right]\Bigg\} \qquad (19)\\
&-(\alpha_{ee}+\alpha_{es})\left(\frac{I_{iet}}{K_{ie,t-1}}-\delta_e\right)-\alpha_{es}\sqrt{\frac{K_{is,t-1}}{K_{ie,t-1}}}\left(\frac{I_{ist}}{K_{is,t-1}}-\delta_s\right)-p_{et}\left(\frac{\Gamma_{iet}}{1-\tau_t}\right),\\
&=u_i+v_{e,t+1}+\omega_{ie,t+1}.
\end{aligned}$$

The Euler equation for structures is symmetric and will be denoted as equation (19)$'$. When strong (log-additive) separability and unrelated adjustment costs are assumed, the Euler equations simplify to a single one for total capital (see, e.g., Hubbard et al. 1995).

We test whether the non-negativity constraint on profits binds in our specification using an approach that is directly comparable to the Euler equation specifications in the literature on liquidity constraints (see the citations in footnote 10). Specifically, we ignore shareholder-level taxes ($\eta_t = \eta_{t+1} = 1$) and parameterize the multipliers, μ, as a linear function of the change in the firm's net worth, defined as cash flow CF:

$$\frac{1+\mu_{i,t+1}}{1+\mu_{it}} = 1 + \frac{\mu_{i,t+1}-\mu_{it}}{1+\mu_{it}} = 1 + \gamma_j \frac{CF_{i,t+1}}{K_{ijt}} = 1 + \Theta_{ij,t+1}. \qquad (20)$$

Then the term in braces in equations (19) and (19)$'$ is multiplied by $(1+\Theta_{ij,t+1})$ instead of the leading term in parentheses.[22] In this formulation γ_j measures the change in the firm's effective discount factor resulting from an increase in internal funds, holding fundamentals constant. When liquidity constraints are binding, high cash flow relaxes

Consistent with the literature, we assume that both "own" adjustment cost terms (α_{ee} and α_{ss}) are positive. We confirm whether convexity holds in our empirical work.

[22]The studies in the literature parameterize the constraints in different ways. Some studies include an intercept term in Θ (Hubbard et al. 1995); others include $\frac{CF_{it}}{K_{i,t-1}}$ or even other variables as additional regressors (Himmelberg 1990).

the constraint, and hence increases (decreases) the effective discount factor (rate), i.e., $\gamma_j > 0$.[23]

We estimate the two Euler equations and the production function simultaneously. The Euler equations are first-differenced to remove the firm-specific error term and year dummies are introduced as regressors for $\upsilon_{j,t+1}$ in each period. The equations are estimated by the generalized method of moments (GMM). The GMM estimator accommodates conditional heteroskedasticity of unknown form in the error terms $\omega_{ij,t+1}$ and ε_{it}.

When the error terms are serially uncorrelated, lagged endogenous variables are valid instruments for the endogenous variables in the three equations. However, first-differencing introduces a first-order moving average error that necessitates using instruments dated at $t-2$ and before. If the model is misspecified the error terms may be serially correlated of higher order, in which case even instruments dated at $t-2$ and before may be invalid. Hence it is important to test for the presence of this higher-order serial correlation. In our empirical results we report the Sargan statistic which is a test of the joint null hypothesis that the model is correctly specified and that the instruments are valid (for further theoretical details see, e.g., Arellano and Bond 1991; Blundell, Bond, Devereux, and Schiantarelli 1992).[24] Unfortunately, it is not possible to test either hypothesis separately. So considerable caution should be exercised in interpreting why the null is rejected — the instruments may be invalid or, more seriously, the model may be misspecified, or both.

4.2 Estimation Results

Our estimation results are contained in tables 2 and 3. In our instrument set, we use lagged endogenous variables, k_e, k_s, v, $\frac{I_e}{K_e}$, $\frac{I_s}{K_s}$, $\frac{Y}{K_e}$, $\frac{Y}{K_s}$, interactions of lagged endogenous variables, and lagged costs of capital, $\widehat{c_e}$, $\widehat{c_s}$, $\widehat{c_e c_s}$, as well as year dummies, industry dummies, and an intercept. We use period $t-3$ values of these variables.[25]

[23]In the literature, $\gamma < 0$ indicates that cash flow relaxes the constraint, because Θ in those studies is equivalent to $-\Theta$ in this study.

[24]Formally, the Sargan statistic is a test that the overidentifying restrictions are asymptotically distributed $\chi^2_{(n-p)}$, where n is the total number of instruments and p is the number of parameters.

[25]When we used period $t-2$ instruments the Sargan statistic increased substantially, suggesting that these instruments are invalid. When we used period $t-4$ and $t-3$ instruments our results were qualitatively unaffected. When we use period $t-4$ instruments, however, there are significantly fewer firms in the

Table 2 presents the parameter estimates from five different specifications of our model. We first estimate equations (19) and (19)′ separately, then together, and finally joint with the production function, equation (15). The production and adjustment cost parameters are reported in the top and bottom panels, respectively. For each equation in the specifications, we use year and industry dummy variables for durable and non-durable goods manufacturing.[26]

The estimates of the Euler equations for equipment and structures are in the first and second columns. Both the estimated equipment and structures capital shares are very small but statistically significant. Both of the estimated adjustment cost parameters are negative and statistically significant, which violates the convexity of the adjustment cost function. The Sargan tests reported at the bottom of the table indicate that the joint null hypothesis that the model is correctly specified and that the instruments are valid is rejected for the equipment equation but not for the structures equation. These initial results show that separately estimating dynamic factor demand equations using more disaggregated data yields poor results.

In column three, we examine whether simultaneously estimating both Euler equations improves the results. In this case, the estimated factor shares are still small and statistically significant. However, the estimated adjustment costs are more promising. The "own" adjustment cost parameters are now both positive, however, only the one on equipment is statistically significant. The "cross" adjustment cost parameter is negative and statistically significant, indicating that investments are complements. However, given these parameter estimates, the adjustment cost function violates convexity. Thus jointly estimating the dynamic factor demands appears not to provide substantially improved results.

sample, so we opted to use only the period $t-3$ information set. In appendix B we discuss the results from additional robustness checks.

[26]We dropped additional industry dummy variables because they were statistically insignificant.

In the final two columns we estimate the dynamic factor demands jointly with the production function.[27] In column four, we estimate all the parameters of the production technology but restrict the adjustment costs of equipment and structures to be unrelated. In column five, we relax this restriction. The Sargan tests indicate that neither specification is rejected. In both cases, all of the parameters of the production technology are statistically significant save one. Hence, strong (log-additive) separability can easily be rejected using a Wald test (which we do not report) on the higher-order production parameters. The Wald statistic at the bottom of the table is a test of the null hypothesis that equipment and structures are weakly separable in the production function (i.e. $\phi_{K_e}\phi_{K_sV} = \phi_{K_s}\phi_{K_eV}$).[28] The null is rejected at the one percent level in column four and at the five percent level in column five. Thus there is qualified evidence that the data reject the key necessary condition to express the aggregate capital stock as an index of multiple capital inputs.

The estimates imply much more reasonable values for the factors shares and adjustment costs (see the discussion below of tables 4, 5, and 6). The parameter estimates on equipment and structures capital are an order of magnitude greater than in the first three specifications. All of the "own" adjustment cost parameter estimates are positive and statistically significant. When the "cross" adjustment cost parameter is estimated in column five, it is negative and statistically significant, capturing the intuition from section 3 that investments are complements.[29] The economically and statistically significant evidence for complementarity of investments raises the possibility that the parameter estimates of the production technology may be biased when interrelated adjustment costs are ignored (column four). Indeed, comparing the production function parameter estimates between the specifications shows that there are a number of

[27]To ensure that the production function is monotonically increasing and strictly quasi-concave, as is required by theory, we checked whether the fitted values of the share equations (marginal products) were positive and that the matrix of substitution elasticities was negative semidefinite at each observation (see Lau 1978). For our preferred specification, column five, all of the observations satisfied monotonicity and only about five percent of them violated quasi-concavity. Hence, the translog function is well behaved in the vast majority of the neighborhood covered by our dataset.

[28]The translog has often been used to test separability (see, e.g., Denny and Fuss 1977). However, Blackorby, Primont, and Russell (1978) show that most flexible functional forms, including the translog, become inflexible when separability restrictions are imposed. In particular, the translog cannot be used to model non-homothetic, non-additive separability, so our test is biased in favor of rejecting the null hypothesis of weak separability. Diewert and Wales (1995) propose two flexible functional forms to address this drawback. Unfortunately, they are impractical since none of the firm-level datasets we know of contain the price data necessary to estimate them.

[29]The parameter estimates indicate that the adjustment cost function is convex.

statistically significant differences. Since substitution possibilities cannot be gauged by casual examination of the parameter estimates, we postpone answering whether the parameter differences result in economically important biases until our discussion of tables 5 and 6.

In table 3 we examine the robustness of our preferred specification in column five. In the first column, we estimate the discount factor. The folk wisdom from dynamic factor demand models is that the estimated discount factor is often economically unreasonable (e.g., the estimated discount factor was usually significantly greater than unity in Altshuler and Cummins 1997). In our specification, however, the discount factor is precisely estimated and economically sensible given that the mean discount rate is 0.05 in our sample. In the second column, we estimate the depreciation rates. The estimated depreciation rate for equipment is 0.153 and for structures is 0.046. The point estimates are very close to the sample means of 0.167 and 0.040, however, for structures, the estimate is imprecise.

Finally, in the last three columns of table 3 we explore the role of internal funds in our model. To maintain comparability with previous studies, we only report estimates from a specification that is the norm in the literature. That is, we replace the leading term in parentheses in the equipment Euler equation with $(1 + \gamma_e \frac{CF_{i,t+1}}{K_{iet}})$ and the leading term in parentheses in the structures Euler equation with $(1 + \gamma_s \frac{CF_{i,t+1}}{K_{ist}})$.[30] The estimate of γ_j measures the change in the firm's effective discount factor resulting from an increase in internal funds. When γ_j is positive an increase in internal net worth, holding investment opportunities constant, increases the effective discount factor (decreases the effective discount rate).

Column three reports the estimates of γ_j in our preferred specification. Neither estimate is positive and statistically significant. In fact, γ_e is negative and statistically significant, which means that an increase in cash flow *decreases* investment. Cummins et al. (1997) also found similar effects of cash flow using a different empirical investment equation, different data, and a variety of estimators. The result merits further investigation but would take this study too far afield. Nevertheless, it is worth noting that it stands in sharp contrast to the prediction from the literature on liquidity

[30]Our qualitative results were unaffected when we included an intercept or $\frac{CF_{it}}{K_{ij,t-1}}$ in $\theta_{ij,t+1}$.

constraints. The qualitative features of the production and adjustment cost parameter estimates are unaffected.

One possible objection to the seemingly counterintuitive effect of cash flow in column three is that the firms in the sample are unlikely to face binding liquidity constraints. To examine whether the result was robust, we estimated the same specification on different samples of firms that are *a priori* more likely to face binding liquidity constraints. There are a number of plausible sample splits that have been used to try and identify these firms. We tried several with similar results and report in column four the estimates from a sample of firms that are in the lowest quintile of the dividend payout ratio. The estimates of γ_j are both negative and statistically significant. The production function parameter estimates on capital are smaller in magnitude than in column three but still statistically significant. This is sensible if the firms in this sample are less capital intensive, as might be expected. The "own" adjustment cost parameter estimates are statistically insignificant, although the "cross" parameter estimate is statistically significant.[31]

The important question is whether our approach can explain why so many studies find evidence for liquidity constraints. In other words, what forms of misspecification could generate estimates of γ_j that are positive and statistically significant. In column five we impose the restrictions that enable heterogeneous types of capital to be aggregated into a single capital aggregate — the production technology is Cobb-Douglas and the investments' adjustment costs are unrelated — despite the evidence to the contrary. In this case, the estimate of γ_e is positive and statistically significant (although the estimate of γ_s is negative and statistically significant). Hence, cash flow may seem to relax a liquidity constraint on equipment investment but, in fact, it may just be correlated with parts of the marginal products of capital and marginal costs of investment that are ignored by assuming that capital is homogeneous.[32] The parameter estimates on capital in the production technology are biased toward zero and the estimates of the "own" adjustment cost parameters are negative and statistically significant, violating convexity of the adjustment cost function. In this case, the Sargan test rejects the joint

[31]The estimates imply marginal adjustment costs that are similar to the ones discussed below for our preferred specification.

[32]Hayashi (1997) has made a similar point about interpreting the evidence for liquidity constraints presented in Hoshi, Kashyap, and Scharfstein (1991).

null that the model is correctly specified and the instruments are valid. This spurious liquidity effect likely plagues every study that purports to find liquidity constraints since the studies in this literature omit the higher-order terms of the production and adjustment cost technologies.

We can use the estimates of the adjustment cost parameters to calculate the marginal adjustment costs of both equipment and structures investment using equation (18). Table 4 presents calculations of these marginal adjustment costs using the sample means of the ratios of net equipment and structures investment to their beginning-of-period capital stock (reported in table 1). The first row is the "own" marginal adjustment cost without taking into account the "cross" effect. The second row is the "cross" effect and the third is "total" marginal adjustment cost.

In the first column of table 4 we use the estimates of the specification in column four of table 2 — in which investments are assumed unrelated — to calculate the marginal adjustment costs. The marginal adjustment cost of adding one dollar of equipment capital is about \$0.08; for structures capital it is about \$0.26. In column two we use our preferred estimates from column five of table 2. In this case, total adjustment costs are about half of those in column one because we incorporate interrelated adjustment costs. In columns three and four of table 4 we use the parameter estimates from the first and second columns of table 3 and find small marginal adjustment costs as well.

Since we do not know of any studies that estimate interrelated adjustment costs using firm data we cannot directly compare our results to those in previous studies.[33] However, we can compare our total marginal adjustment costs. A common empirical failing of the neoclassical model has been that marginal adjustment costs are implausibly large (Chirinko 1993a).[34] In contrast, when we incorporate interrelated adjustment costs, our estimates imply some of the smallest marginal adjustment costs in the literature. Thus the dynamic response of investment to policy changes will be relatively rapid.

[33]In general, there is only weak evidence for interrelated adjustment costs in aggregate time-series data (see, e.g., Shapiro 1986). However, our results suggest that this negative finding may reflect aggregation bias. Using more disaggregated data, Bernstein and Nadiri (1989) estimate how research and development and investment are interrelated and find that there are significant spillovers in some industries.

[34]For example, Summers' (1981) estimates imply values for α_{ee} and α_{ss} in excess of 50. In a number of recent studies estimated marginal adjustment costs are more reasonable (see, e.g., Cummins et al. 1994; Cummins et al. 1995; Cummins et al. 1997; and the survey in Hassett and Hubbard 1997).

Tables 5 and 6 present the price (PES_{X_i,X_j}) and Morishima (MES_{X_i,X_j}) elasticities of substitution between factors X_i and X_j.[35] In table 5 the elasticities of input substitution are calculated at the sample means using the parameter estimates in column four of table 2. Table 6 uses the parameter estimates in column five of table 2.

There are two principal findings that the specifications share. First, capital demands are relatively price elastic, consistent with the result that adjustment costs are modestly sized. Second, the Morishima elasticities indicate that all the factors are relatively strong substitutes (defined as greater than unit elastic substitutes).[36]

There are two principle differences between the tables. First, factor substitution possibilities are greater — sometimes by even more than 50 percent — when adjustment costs are interrelated. Second, in the bottom rows of tables we report the factor shares and returns to scale. In table 5 (table 6) the shares of equipment and structures are about 0.09 (0.07) and 0.07 (0.05), respectively, and the share of the variable input is about 0.88 (0.89). The returns to scale are 1.046 in table 5 and 0.997 in table 6. These findings suggest that when interrelated adjustment costs are ignored, the complementarity of investments is captured as greater complementarity between factors of production and increasing returns to scale.

5 Policy Analysis

In this section, we use our theoretical model and our parameter estimates to study the effects of various policy changes on the steady state and dynamic behavior of a representative firm. We can use our model to derive a system of first-order differential equations in K_j and q_j using the capital stock accounting identities, equation (5),

[35]The Morishima elasticity of substitution is the log-derivative of an input quantity ratio (taken from the compensated input demands) in the ith coordinate direction. The elasticities are related in the following way:

$$PES_{X_i,X_j} = \frac{\partial \ln X_i}{\partial \ln p_j}; \qquad MES_{X_i,X_j} = PES_{X_j,X_i} - PES_{X_i,X_i}$$

where X_i is the ith factor input and p_j is the jth factor price.

[36]The price and Allen elasticities of substitution are incorrect measures of the ease of substitution possibilities when there are more than 2 factors of production (Blackorby and Russell 1981, 1989). Our price elasticities — and by extension our Allen elasticities — indicate that equipment and structures are complements when in fact the theoretically correct Morishima elasticities show that they are rather strong substitutes. Our findings then are evidence that Blackorby and Russell's theoretical results can be quite important in empirical work.

the first-order conditions for investments, equation (9), and the Euler equations (10). Assuming the non-negativity constraint on profits does not bind ($\mu_t = 0, \ \forall t$), we can rearrange equation (9) to obtain the first-order differential equations governing the equipment and structures capital stocks:

$$\frac{\dot{K}_e}{K_e} = \frac{(\alpha_{ss} + \alpha_{es})(q_e - \eta\Gamma_e)p_e - \alpha_{es}(q_s - \eta\Gamma_s)p_s\sqrt{\frac{K_s}{K_e}}}{\eta(1-\tau)(\alpha_{ee}\alpha_{ss} + \alpha_{ee}\alpha_{es} + \alpha_{ss}\alpha_{es})};$$
$$\frac{\dot{K}_s}{K_s} = \frac{(\alpha_{ee} + \alpha_{es})(q_s - \eta\Gamma_s)p_s - \alpha_{es}(q_e - \eta\Gamma_e)p_e\sqrt{\frac{K_e}{K_s}}}{\eta(1-\tau)(\alpha_{ss}\alpha_{ee} + \alpha_{ss}\alpha_{es} + \alpha_{ee}\alpha_{es})}. \tag{21}$$

The remaining differential equations are obtained by rearranging the Euler equations. We rewrite equation (10) using equation (5):

$$\dot{q}_e = q_e(\rho_e + \delta_e) - \frac{\eta(1-\tau)}{p_e}\left[\frac{Y}{K_e}\left(\phi_{K_e} + \phi_{K_eK_e}k_e + \phi_{K_eK_s}k_s + \phi_{K_eV}v\right)\right]$$
$$-\frac{1}{2}\left[\frac{(\alpha_{ss} + \alpha_{es})(q_e - \eta\Gamma_e)p_e - \alpha_{es}(q_s - \eta\Gamma_s)p_s\sqrt{\frac{K_s}{K_e}}}{\eta(1-\tau)(\alpha_{ee}\alpha_{ss} + \alpha_{ee}\alpha_{es} + \alpha_{ss}\alpha_{es})} + \delta_e\right](q_e - \eta\Gamma_e);$$
$$\dot{q}_s = q_s(\rho_s + \delta_s) - \frac{\eta(1-\tau)}{p_s}\left[\frac{Y}{K_s}\left(\phi_{K_s} + \phi_{K_sK_s}k_s + \phi_{K_eK_s}k_e + \phi_{K_sV}v\right)\right]$$
$$-\frac{1}{2}\left[\frac{(\alpha_{ee} + \alpha_{es})(q_s - \eta\Gamma_s)p_s - \alpha_{es}(q_e - \eta\Gamma_e)p_e\sqrt{\frac{K_e}{K_s}}}{\eta(1-\tau)(\alpha_{ss}\alpha_{ee} + \alpha_{ss}\alpha_{es} + \alpha_{ee}\alpha_{es})} + \delta_s\right](q_s - \eta\Gamma_s). \tag{22}$$

Finally, the model is closed by the production technology, equation (15), and the first-order condition for variable input demand, equation (6).

We use these equations to simulate the effects of various tax policy changes on the steady-state and dynamic behavior of output and the factor inputs. To provide a basis for evaluating our estimated model — in which factors are greater than unit elastic substitutes and investments are complements — we compare it to one in which production is Cobb-Douglas and adjustment costs are unrelated (which we will call the CD model).

5.1 Steady State Analysis

We solve for the baseline steady state of our model using the structural parameter estimates in column five of table 2 as well as the 1992 values of the factor prices, average deprecations, average tax parameters, and the discount rate. To compare our model to the CD model, we calibrate the CD production parameters so that the baseline marginal products of the factors are equal to those in our model. We then compare the effects of different policy experiments to the baseline steady states. All of the experiments are equivalent in the sense that they have the same percentage effect on the equipment cost of capital. Alternatively, we could have used the total cost of capital as a benchmark. Regardless of which one we choose, however, the qualitative result is unchanged: seemingly identical tax changes have different effects.

The steady state results for the CD model are presented in the top panel of table 7 and the results for our model are in the bottom panel.[37] Each entry in the table is the percentage change in the variable from its baseline value in each panel. We consider the effects on the value of the inputs in the first three columns, and the effects on the factor shares in the last three columns.

The first experiment is a five percentage point increase in the ITC for equipment which causes a seven percent decrease in the equipment cost of capital while leaving the structures cost of capital unaffected. As expected, the share of equipment increases in both models. But since we do not force inputs to be unit elastic substitutes in our model, relative to the CD model, the increase in equipment's share is greater, while the decrease in structures' share is less. In addition, despite the fact that we parameterized the CD model so that the marginal products in both models were equal, the increase in each of the factor inputs in our model is greater (e.g., the steady state equipment (structures) capital stock is five (three) percentage points greater in our model).

In the second experiment, we decrease the corporate tax rate which has two effects on the costs of capital (see equation (12)). First, the cut makes investment more desirable by increasing the after-tax marginal product of capital (i.e., decreases $(1-\tau)$ in the denominator of the cost of capital). Countervailing this effect, the cut makes investment less desirable by decreasing the present value of depreciation allowances (i.e., increases Γ in the numerator of the cost of capital). Given the relatively generous depreciation allowances granted equipment, D_e, the corporate tax rate has to be cut

[37] Although we only consider tax policy experiments, the model can be used to analyze the effects of other changes as well. For example, a decrease in the price of equipment (e.g., due to technological change) has the same effects as our first experiment in which we increase the ITC for equipment; a cut in the discount rate has the same effects as our second experiment in which we decrease the corporate tax rate.

to 6.6 percent to yield a 7 percent drop in the equipment cost of capital. Since depreciation allowances for structures are relatively stingy, the countervailing effect is relatively less important, so the structures factor share increases substantially in this experiment. As in the first experiment, the responses of both the steady state values and the factor shares are greater in our model than in the CD model.

In the third experiment, we decrease the corporate tax rate but simultaneously increase depreciation allowances so that Γ_j is unaffected. In the CD model, this results in equal increases in the steady-state values of equipment and structures and in their factor shares. In contrast, the greater substitutability in our model results in an increase in the structures share that is more than double the increase in the equipment share.

There are two lessons to draw from the steady state simulations. First, changes in tax parameters that have the same effect on the cost of capital can have very different effects in a model with multiple capital goods. Second, the steady state responses to policy changes are larger in a model in which factors are relatively strong substitutes.

5.2 Dynamic Analysis

To study the dynamic effects of our policy experiments, we assume that the representative firm is in the baseline steady state and solve for the stable manifolds describing the transition to the new steady states. We use the multiple shooting algorithm to solve for the transition paths defined by the differential equations (21) and (22). This is computationally quite intensive since we have to search over a fine grid to find initial conditions for two, two-point boundary value problems that are interrelated and saddle path stable.

In figures 4 and 5 we compare the dynamic effects of the policy experiments in the CD model and in our model. We plot the growth rates of equipment and structures for the first 25 years following the policy change. We depict the growth rates relative to the baseline steady state, calculated as the ratio of the first difference of the capital stock to the baseline steady state capital stock.[38] To compare our model to the CD model, we calibrate the CD adjustment cost parameters so that the baseline marginal adjustment costs of investment are equal to those in our model. Then the differences

[38] Alternatively, we could define the growth rate as the difference between the capital stock in year t and the baseline steady state capital stock divided by the baseline steady-state capital stock.

between the two model can be solely attributed to greater factor substitutability and complementarity in the adjustment costs.

We first consider the effects of the tax policy experiments in the CD model. When the ITC is increased, the growth of equipment is large relative to the anemic response in structures. This is sensible given that the marginal adjustment cost of structures investment is about four times larger than the marginal adjustment cost of equipment investment. When the corporate tax rate is cut, the growth rates of both equipment and structures are greater than in the first experiment. Since the cut decreases structures depreciation allowances by less than it decreases equipment allowances, the growth in structures is greater. Finally, the corporate tax cut that leaves depreciation allowances unaffected results in dynamics similar to the first experiment: equipment grows rapidly at first while structures grows relatively slowly.

In contrast to the results for the ITC increase in CD model, in our model, the growth in equipment is accompanied by significant growth in structures. The explanation comes from the complementarity of equipment and structures in the adjustment cost function ($\alpha_{es} < 0$). If the interrelated adjustment cost parameter is negative, growth in one type of capital leads to an acceleration in the growth of the other type of capital (see equation (21)).[39] This means that regardless of the steady state effects of policy changes, investments will tend to move together. As a result, relative to a model in which adjustment costs are unrelated, complementary adjustment costs lead to more robust responses to policy changes. The second and third experiments provide additional evidence for this. In the first years of the transition, the growth rates for both equipment and structures are larger and more closely correlated than in the CD model.

6 Conclusion

Studies in the investment literature typically assume that capital is homogeneous. In our model, we accommodate flexible interactions among different types of capital and variable inputs in the firms' production and adjustment cost technologies. The ideal dataset for estimating our model would contain very disaggregated data on the different

[39]If equipment and structures investment are substitutes ($\alpha_{es} > 0$) equipment (structures) capital growth dampens structures (equipment) capital growth on the steady state path, in which case adjustment to the steady state would be slower than in the CD model.

factors of production. Unfortunately, such rich data do not exist so we can only make modest progress in characterizing the features of these complicated technologies. Nevertheless, our results suggest that our approach is promising. Using firm-level panel data that separates capital into its two main components, equipment and structures, we are able to suggest some explanations for the empirical failings of the neoclassical model of investment. Our results also suggest some directions for future research.

We reject the necessary conditions to estimate a homogenous capital goods model. According to our estimates, equipment and structures are not perfect substitutes, and yet we also find that there are substantial opportunities to substitute between different types of capital and variable inputs in the production process. Our estimates of the adjustment costs suggest that different types of investment are complementary — increases in one type of investment decrease the adjustment costs of the other type of investment. Furthermore, we show that when this feature of the adjustment cost technology is ignored estimates of factor substitution in production are biased downward, and estimates of adjustment costs are biased upward. We also investigate whether investment is sensitive to changes in internal net worth. We find that holding constant investment opportunities, an increase in internal net worth, as measured by cash flow, increases investment only when capital heterogeneity is restricted. Hence cash flow may matter in other studies not because it parameterizes a liquidity constraint, but because it is correlated with features of the technology that are ignored by assuming that capital is homogeneous.

Our simulations demonstrate the importance of including interrelated production and adjustment technologies in models designed to evaluate the impact of changes in tax policy on investment behavior. Tax changes that have identical effects in a model with homogeneous capital have much different responses when capital is heterogeneous. In addition, regardless of the steady state effect of policy, investment in different types of capital will tend to be coordinated. Our simulations show that this complementarity in the technology of investment is an economically significant magnification and propagation mechanism. This provides a technological explanation for why investment is coordinated through booms and busts and thus would contribute to explaining wider swings in output in response to shocks.

There are many issues our analysis either does not attempt to address or cannot address. In the estimation we have to rely on data that are aggregated at the firm level. We also ignored certain features of the data such as the lumpiness of capital goods and the vintage structure of capital. Because the model is partial equilibrium, our simulation results are only illustrative. It may be possible to incorporate the features of our model into a dynamic general equilibrium model, but given the computational complexity of our deterministic partial equilibrium simulations we leave this task to future research. A simpler extension of the simulation model would be to relax the assumption of perfect foresight and incorporate uncertainty over the after-tax price of capital (see, e.g., Bizer and Judd 1989). This would enable the simulation to fit the data better but the qualitative features of the deterministic problem are unlikely to be affected. Another extension along these lines would be to incorporate uncertainty and periodically binding constraints. This, however, would significantly complicate the numerical solution method (see, e.g., McGrattan 1996). In spite of these drawbacks, our approach illustrates that dynamic models with heterogeneous capital can be used to better understand investment behavior and its response to policy changes.

A Dataset Construction

The variables we use are defined as follows. We use three definitions of capital from Compustat: total capital is data item 8; equipment capital is data item 156; and structures capital is data item 155. The replacement value of each capital stock is calculated using the standard perpetual inventory method with the initial observation set equal to the book value of the firm's first reported observation. The depreciation rates used for each type of capital are based on Hulten and Wykoff (1981). Net investment is the change in each capital stock. Gross investment in total capital is defined as capital expenditures (data item 30). Gross investment in equipment and structures is the sum of the change in the capital stock and depreciation.

Gross output is the sum of sales (data item 9) and the change in finished goods inventory (data item 78). Variable factor input is the sum of cost of goods sold (data item 41) and, when reported, selling, general, and administrative expense (data item 189). Labor expense is included in these measures.[40] Value added is gross output less variable input. Cash flow is the sum of net income (data item 18) and depreciation (data item 14).

The total capital stock is deflated by the nonresidental fixed investment deflator. The equipment and structures capital stocks are deflated by the nonresidential producers' durable equipment and structures deflators, respectively. Output and cash flow are deflated by the GDP deflator. These price deflators are obtained from Citibase. We use Compustat data on the firms' S&P bond rating and dividend payouts to split the sample, isolating those firms that may *a priori* face financial constraints.

The nominal after-tax required rate of return on capital, r_t, is constructed as follows. The return on the S&P bond associated with the firm's Compustat bond rating (data item 280) is taken from Citibase. We assume that the bond rating is BAA for firms that do not report a rating. We then construct the required rate of return as the ratio of the bond return to $(1 - z_t)$. Expected inflation is the annual average of the monthly values reported by the Livingston Survey. The tax parameters are updated from those used in Cummins, Hassett, and Hubbard (1994).

[40] Labor and related expense (data item 42) is not reported frequently enough to include it as a separate variable factor of production.

We delete observations when (1) the ratio of net equipment (structures) investment to beginning-of-period equipment (structures) capital is greater than unity or less then -0.75; (2) the ratio of output to beginning-of-period equipment or structures capital is greater than 65; (3) value added is negative. These types of rules are common in the literature. The first cut-off is intended to eliminate observations that reflect especially large mergers, extraordinary firm shocks, or Compustat coding errors. The second and third are intended to remove firms with capital stocks that are relatively small compared to their output and value added. Our results are robust to other similar rules for deleting outliers.

B Robustness of Empirical and Simulation Results

In this appendix we report how our conclusions are affected by a number of alternative specifications. For the estimation results we examined changes in: instrument sets; how the parameters are identified; and alternative functional forms. For the simulation results we examined changes in parameter values and initial conditions.

B.1 Robustness of Empirical Results

We experimented with many different variables in the instrument sets. We found that including some variables led to rejections of the Sargan test and economically unreasonable parameter estimates. For example, including period $t-2$ variables almost always led to rejections of the null. Given our success with period $t-3$ and $t-4$ dated instruments, we interpreted these rejections as evidence of residual serial correlation. This sensitivity to timing is common in investment equations estimated with GMM (see, e.g., Blundell, Bond, Devereux, and Schiantarelli 1992). In general, when we used alternative instrument sets that did not lead to rejections of the null our qualitative results were similar to those reported in table 2.

A potential criticism of our structural model is that the production and adjustment cost parameters are identified by an accelerator effect introduced by $\frac{Y_{it}}{K_{iet}}$ and $\frac{Y_{it}}{K_{ist}}$ in the marginal products of capital. To examine this possibility we shut down the variance in these variables by setting them equal to their sample means. We found that the precision of the estimates was decreased but that they were still statistically significant from zero. More importantly, the qualitative results were unaffected. Thus our estimates are not capturing an accelerator effect.

A similar potential criticism is that the adjustment cost parameters are not identified, as theory suggests they should be, by the after-tax price of capital. To examine this possibility we performed two experiments: the first eliminates taxes and investment incentives, the "no tax" model; and the second eliminates prices completely by setting them equal to unity, the "no price" model. In general these specifications performed very poorly. We found that parameter estimates of the adjustment cost function violated convexity, implying negative marginal adjustment costs. In both these specifications the Sargan test was rejected. Thus in both specifications we can reject the joint null that the model is correctly specified and that the instruments are valid. Unfortunately, this is not solely a test of the "no tax" or "no price" models. However, the result that the adjustment cost parameters violate convexity suggests that both taxes and factor prices have an important role in identifying the model.[41]

We examined whether alternative functional forms for adjustment costs affected our results. Specifically, we assumed an adjustment cost function on net investment with the feature that adjustment costs affect the steady state capital stock. The estimates of this model produced total marginal adjustment costs, elasticities of substitution, and factor shares similar to those in tables 4 and 6. We also experimented with an adjustment cost function on gross investment by setting $\delta_j = 0$ in equation (17). It proved impossible to find an instrument set that did not reject the Sargan test so we interpreted the resulting estimates with great skepticism: While the production function parameter estimates were economically reasonable and statistically significant, the parameter estimates of the adjustment cost function varied widely and were often statistically insignificant.

B.2 Robustness of Simulation Results

We considered the effects of a number of changes in the parameters of the policy simulations that we did not discuss. For example, we relaxed the assumption that the

[41] We follow Shapiro (1986) in conducting the latter two robustness tests of shutting down the variance in output and eliminating taxes and factor prices from the model.

interest rate is insensitive to changes in tax policy without qualitatively affecting the comparative results between the CD model and our model.

Our analysis was performed for a representative firm. We examined how the composition of the firm's capital affects the dynamic response to policy changes by experimenting with different initial ratios of the equipment to structures capital stock. In general, when the initial structures capital stock is larger (smaller) than the equipment capital stock, the marginal product of structures capital is lower (higher) and, consequently, the response of structures investment to policy changes is smaller (larger). In terms of figures 4 and 5 this effect can be seen as rightward shift in the equipment transition path. If less mature firms have greater initial structures capital stocks — as shown by Boddy and Gort (1994) — this means that we expect their equipment investment response to be larger than for mature firms.

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Table 1: Means, Medians, and Standard Deviations of Selected Sample Variables

Year	Y_t	V_t	$K_{e,t-1}$	$K_{s,t-1}$	$I_{et}/K_{e,t-1}$	$I_{st}/K_{s,t-1}$	$\widehat{c_{et}}$	$\widehat{c_{st}}$
1981	2182	1890	367	148	0.203	0.052	0.270	0.153
	(569)	(491)	(55)	(38)	(0.183)	(0.016)	(0.273)	(0.154)
	[5539]	[4906]	[1151]	[358]	[0.160]	[0.158]	[0.012]	[0.007]
1982	2015	1751	367	146	0.222	0.083	0.328	0.310
	(513)	(447)	(54)	(38)	(0.194)	(0.038)	(0.331)	(0.311)
	[5189]	[4494]	[1213]	[374]	[0.174]	[0.174]	[0.013]	[0.005]
1983	2093	1797	369	150	0.242	0.110	0.289	0.165
	(486)	(408)	(51)	(38)	(0.215)	(0.067)	(0.292)	(0.165)
	[5920]	[4930]	[1225]	[392]	[0.169]	[0.185]	[0.012]	[0.003]
1984	2094	1790	348	154	0.284	0.118	0.269	0.174
	(518)	(447)	(55)	(39)	(0.254)	(0.078)	(0.272)	(0.174)
	[6077]	[5170]	[1076]	[394]	[0.174]	[0.180]	[0.012]	[0.003]
1985	2121	1825	358	162	0.287	0.150	0.223	0.167
	(522)	(442)	(61)	(39)	(0.263)	(0.117)	(0.228)	(0.168)
	[6516]	[5578]	[1044]	[414]	[0.181]	[0.187]	[0.014]	[0.007]
1986	2202	1907	391	185	0.253	0.129	0.072	0.030
	(573)	(486)	(66)	(43)	(0.233)	(0.089)	(0.077)	(0.035)
	[6709]	[5931]	[1180]	[506]	[0.192]	[0.198]	[0.015]	[0.015]
1987	2379	2042	421	206	0.248	0.123	0.279	0.132
	(631)	(541)	(74)	(47)	(0.226)	(0.085)	(0.285)	(0.134)
	[6796]	[5982]	[1360]	[576]	[0.174]	[0.154]	[0.016]	[0.008]
1988	2489	2101	432	221	0.220	0.097	0.269	0.144
	(635)	(560)	(80)	(47)	(0.197)	(0.069)	(0.273)	(0.145)
	[7455]	[6236]	[1440]	[627]	[0.179]	[0.191]	[0.014]	[0.007]
1989	2473	2092	454	226	0.229	0.079	0.257	0.142
	(617)	(507)	(83)	(51)	(0.208)	(0.048)	(0.262)	(0.143)
	[7319]	[6098]	[1617]	[631]	[0.168]	[0.159]	[0.014]	[0.009]
1990	2537	2163	482	238	0.233	0.120	0.259	0.174
	(627)	(529)	(85)	(53)	(0.223)	(0.085)	(0.261)	(0.172)
	[7275]	[6190]	[1676]	[652]	[0.165]	[0.173]	[0.031]	[0.038]
1991	2483	2159	532	258	0.188	0.071	0.255	0.171
	(609)	(527)	(94)	(59)	(0.182)	(0.053)	(0.258)	(0.171)
	[6921]	[6151]	[1835]	[698]	[0.153]	[0.155]	[0.018]	[0.018]
1992	2516	2177	556	271	0.216	0.091	0.235	0.105
	(643)	(542)	(98)	(60)	(0.195)	(0.057)	(0.239)	(0.105)
	[7037]	[6241]	[1956]	[722]	[0.149]	[0.151]	[0.013]	[0.008]
Total	2314	1988	435	204	0.236	0.103	0.246	0.148
	(584)	(498)	(74)	(46)	(0.214)	(0.070)	(0.261)	(0.154)
	[6627]	[5722]	[1481]	[560]	[0.172]	[0.172]	[0.060]	[0.061]

The data are in 1987 dollars. Medians of the variables are in parentheses below the means. Standard deviations of the variables are in square brackets below the means. Output is Y_t. Variable input is V_t. Beginning-of-period equipment and structures capital stocks are $K_{e,t-1}$ and $K_{s,t-1}$, respectively. The ratios of equipment and structures investment to beginning-of-period capital stock are $I_{et}/K_{e,t-1}$ and $I_{st}/K_{s,t-1}$, respectively. The equipment and structures costs of capital are $\widehat{c_{et}}$ and $\widehat{c_{st}}$, respectively (see equation (12)).

Table 2: GMM Estimates of the Parameters of the Production and Adjustment Cost Technologies (1981–1992)

	Model Specification: Equations Estimated				
	(19)	(19)′	(19), (19)′	(15), (19), (19)′	(15), (19), (19)′
Parameter	(1)	(2)	(3)	(4)	(5)
Production Function					
ϕ_{K_e}	0.010 (0.000)	—	0.009 (0.002)	0.124 (0.003)	0.145 (0.004)
ϕ_{K_s}	—	0.007 (0.002)	0.008 (0.003)	0.106 (0.006)	0.090 (0.006)
ϕ_V	—	—	—	0.751 (0.008)	0.753 (0.008)
$\phi_{K_eK_e}$	—	—	—	0.036 (0.001)	0.038 (0.001)
$\phi_{K_sK_s}$	—	—	—	0.030 (0.002)	0.031 (0.002)
ϕ_{VV}	—	—	—	0.065 (0.002)	0.067 (0.002)
$\phi_{K_eK_s}$	—	—	—	0.002 (0.000)	-0.000 (0.001)
ϕ_{K_eV}	—	—	—	-0.035 (0.001)	-0.040 (0.001)
ϕ_{K_sV}	—	—	—	-0.027 (0.002)	-0.027 (0.002)
Adjustment Cost Function					
α_{ee}	-0.403 (0.124)	—	5.76 (1.86)	1.17 (0.314)	5.35 (1.96)
α_{es}	—	—	-3.80 (1.09)	—	-2.72 (1.11)
α_{ss}	—	-3.52 (1.29)	3.86 (3.05)	4.08 (1.70)	9.42 (3.42)
Year Effects	Yes	Yes	Yes	Yes	Yes
Industry Effects	Yes	Yes	Yes	Yes	Yes
Wald statistic p-value	—	—	—	6.70 (0.010)	3.94 (0.047)
Sargan statistic p-value	1955 (1.00)	23.5 (0.00)	74.7 (0.00)	652 (0.00)	451 (0.00)
Number of Observations	4317	4317	4317	4317	4317

Asymptotic standard errors are in parentheses. Standard errors and test statistics are robust to general time-series and cross-section heteroskedasticity. The instrument set contains an intercept, year dummies, industry dummies, and period $t-3$ values of k_e, k_s, v, $k_e v$, $k_e k_s$, $k_s v$, $\frac{I_e}{K_e}$, $\frac{I_s}{K_s}$, $\frac{I_e}{K_e}\frac{I_s}{K_s}$, $\frac{Y_e}{K_e}$, $\frac{Y_s}{K_s}$, $\frac{Y_e}{K_e}\frac{Y_s}{K_s}$, $\widehat{c_e}$, $\widehat{c_s}$, $\widehat{c_e}\widehat{c_s}$. The Wald statistic is a test of the null hypothesis that equipment and structures are weakly separable in the production function (i.e. $\phi_{K_e}\phi_{K_sV} = \phi_{K_s}\phi_{K_eV}$). The Sargan statistic is a test of the overidentifying restrictions asymptotically distributed $\chi^2_{(n-p)}$, where n is the number of moments and p is the number of parameters. The number of moments in each specification is equal to the number of instruments (29 in all cases) multiplied by the number of years in the panel (12 in all cases) and the number of equations estimated (between one and three). The number of parameters differs in each specification. The significance levels of the tests are in parentheses below the statistic.

Table 3: GMM Estimates of the Discount Factor, Depreciation Rates, and Value of Internal Funds as well as Technological Parameters (1981–1992)

	Model Specification: Equations Estimated				
	(15), (19), (19)′	(15), (19), (19)′	(15), (19), (19)′	(15), (19), (19)′	(15), (19), (19)′
Parameter	(1)	(2)	(3)	(4)	(5)
β	0.916 (0.016)	—	—	—	—
δ_e	—	0.153 (0.030)	—	—	—
δ_s	—	0.046 (0.058)	—	—	—
γ_e	—	—	-0.112 (0.031)	-0.139 (0.069)	0.130 (0.013)
γ_s	—	—	0.024 (0.023)	-0.042 (0.014)	-0.350 (0.015)
Production Function					
ϕ_{K_e}	0.147 (0.005)	0.147 (0.005)	0.143 (0.004)	0.078 (0.010)	0.003 (0.001)
ϕ_{K_s}	0.100 (0.005)	0.088 (0.007)	0.096 (0.007)	0.075 (0.006)	0.054 (0.002)
ϕ_V	0.739 (0.007)	0.753 (0.008)	0.747 (0.009)	0.859 (0.021)	0.941 (0.002)
$\phi_{K_eK_e}$	0.038 (0.001)	0.038 (0.001)	0.034 (0.002)	0.020 (0.003)	—
$\phi_{K_sK_s}$	0.030 (0.002)	0.031 (0.002)	0.031 (0.003)	0.020 (0.002)	—
ϕ_{VV}	0.070 (0.002)	0.067 (0.002)	0.068 (0.002)	0.038 (0.005)	—
$\phi_{K_eK_s}$	-0.001 (0.001)	0.000 (0.001)	0.001 (0.001)	-0.000 (0.002)	—
ϕ_{K_eV}	-0.040 (0.001)	-0.040 (0.001)	-0.037 (0.001)	-0.020 (0.003)	—
ϕ_{K_sV}	-0.027 (0.001)	-0.026 (0.002)	-0.023 (0.002)	-0.020 (0.002)	—
Adjustment Cost Function					
α_{ee}	5.06 (1.66)	5.67 (2.16)	8.71 (1.65)	-0.625 (0.529)	-0.302 (0.135)
α_{es}	-2.05 (0.888)	-2.92 (1.26)	-4.97 (0.961)	0.970 (0.303)	—
α_{ss}	6.34 (2.95)	10.2 (3.72)	14.2 (2.97)	-1.17 (0.603)	-5.51 (0.565)
Year Effects	Yes	Yes	Yes	Yes	Yes
Industry Effects	Yes	Yes	Yes	Yes	Yes
Sargan statistic p-value	434 (0.00)	452 (0.00)	438 (0.00)	81.3 (0.00)	2891 (1.00)
Number of Observations	4317	4317	4317	863	4317

See notes to table 2.

Table 4: Estimated Marginal Adjustment Costs of Investment

	Unrelated Adjustment Costs (1)		Interrelated Adjustment Costs (2)	
Source of Cost	Equipment	Structures	Equipment	Structures
Own	0.080	0.255	0.369	0.589
Cross	—	—	-0.328	-0.434
Total	0.080	0.255	0.041	0.155

	Interrelated Adjustment Costs (3)		Interrelated Adjustment Costs (4)	
Source of Cost	Equipment	Structures	Equipment	Structures
Own	0.320	0.353	0.391	0.638
Cross	-0.224	-0.297	-0.352	-0.466
Total	0.096	0.056	0.039	0.171

The marginal adjustment costs are calculated by substituting the adjustment cost parameter estimates in columns four and five of table 2 and one and two of table 3 into equation (18) and evaluating at the sample means.

Table 5: Elasticities of Input Substitution and Factor Shares: Translog Production, Unrelated Adjustment Costs

Input	Equipment (K_e)	Structures (K_s)	Variable Input (V)
		Price Elasticities ($PES_{X_iX_j}$)	
Equipment (K_e)	-1.62	-0.37	1.66
Structures (K_s)	-0.05	-1.79	1.84
Variable Input (V)	0.17	0.14	-0.31
		Morishima Elasticities ($MES_{X_iX_j}$)	
Equipment (K_e)	—	1.57	1.79
Structures (K_s)	1.75	—	1.93
Variable Input (V)	1.96	2.14	—
Factor Share	0.090	0.066	0.890

Elasticities of input substitution and factor shares are calculated from the production parameter estimates in column four of table 2.

Table 6: Elasticities of Input Substitution and Factor Shares: Translog Production, Interrelated Adjustment Costs

Input	Equipment (K_e)	Structures (K_s)	Variable Input (V)
		Price Elasticities ($PES_{X_i X_j}$)	
Equipment (K_e)	-2.22	-0.06	2.28
Structures (K_s)	-0.09	-2.78	2.87
Variable Input (V)	0.19	0.16	-0.35
		Morishima Elasticities ($MES_{X_i X_j}$)	
Equipment (K_e)	—	2.12	2.40
Structures (K_s)	2.72	—	2.94
Variable Input (V)	2.63	3.22	—
Factor Share	0.071	0.049	0.876

Elasticities of input substitution and factor shares are calculated from the production parameter estimates in column five of table 2.

Table 7: Steady State Effects of Tax Reform

Model	Policy Change	Steady State Values K_e	K_s	V	Steady State Factor Shares K_e	K_s	V
Cobb-Douglas Production	ITC Decrease	0.35	0.26	0.26	0.055	-0.019	-0.019
	Corporate Tax Decrease	1.75	2.24	1.56	-0.053	0.12	-0.12
	Corporate Tax Decrease Depreciation Unaffected	0.68	0.68	0.56	0.022	0.022	-0.049
Translog Production	ITC Decrease	0.40	0.29	0.26	0.07	-0.017	-0.035
	Corporate Tax Decrease	2.38	3.51	2.07	-0.11	0.20	-0.19
	Corporate Tax Decrease Depreciation Unaffeced	0.80	0.86	0.63	0.018	0.048	-0.08

The simulations use the parameter estimates in column five of table 2 and the 1992 values of the factor prices, average deprecations, average tax parameters, and the discoun: ~ate. The entries are the percentage changes in the variables from their baseline values in each panel.

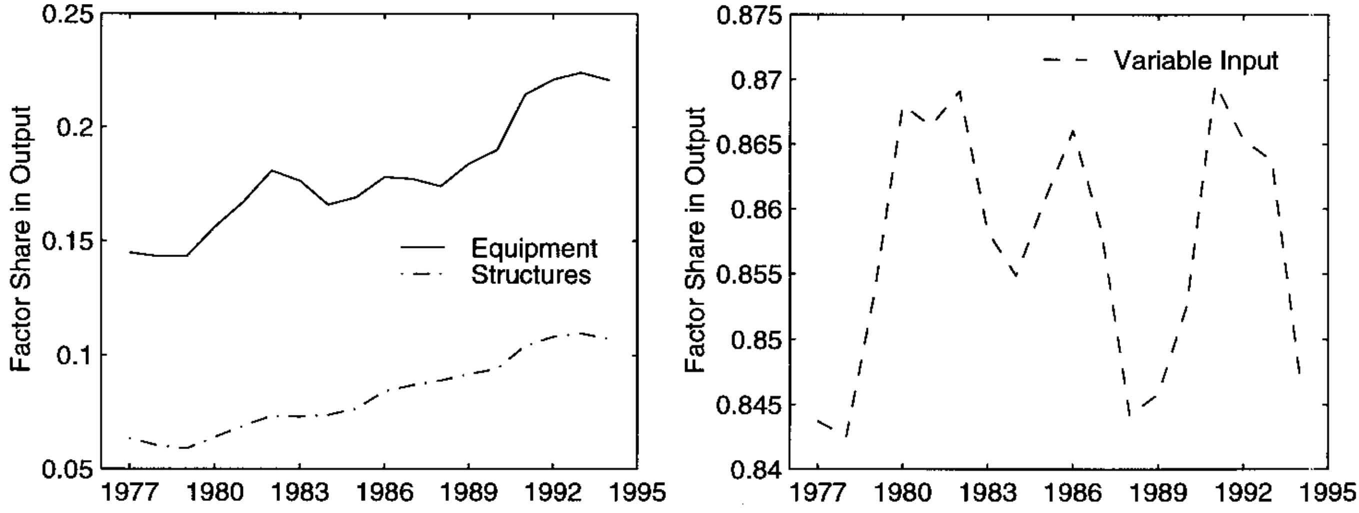

Figure 1: Shares of Equipment, Structures, and the Variable Input in Output

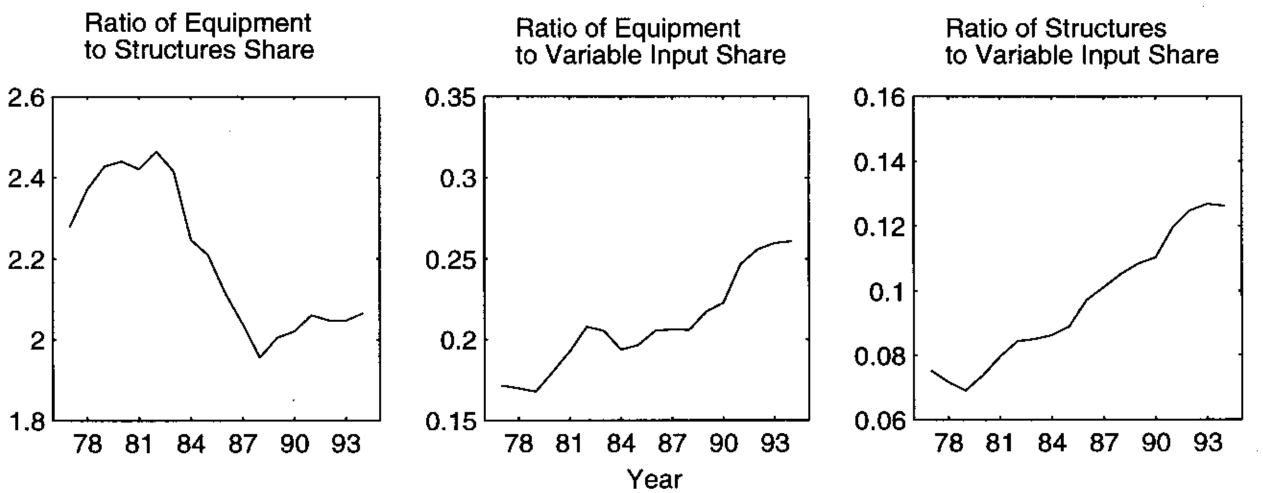

Figure 2: Relative Shares of Equipment, Structures, and the Variable Input

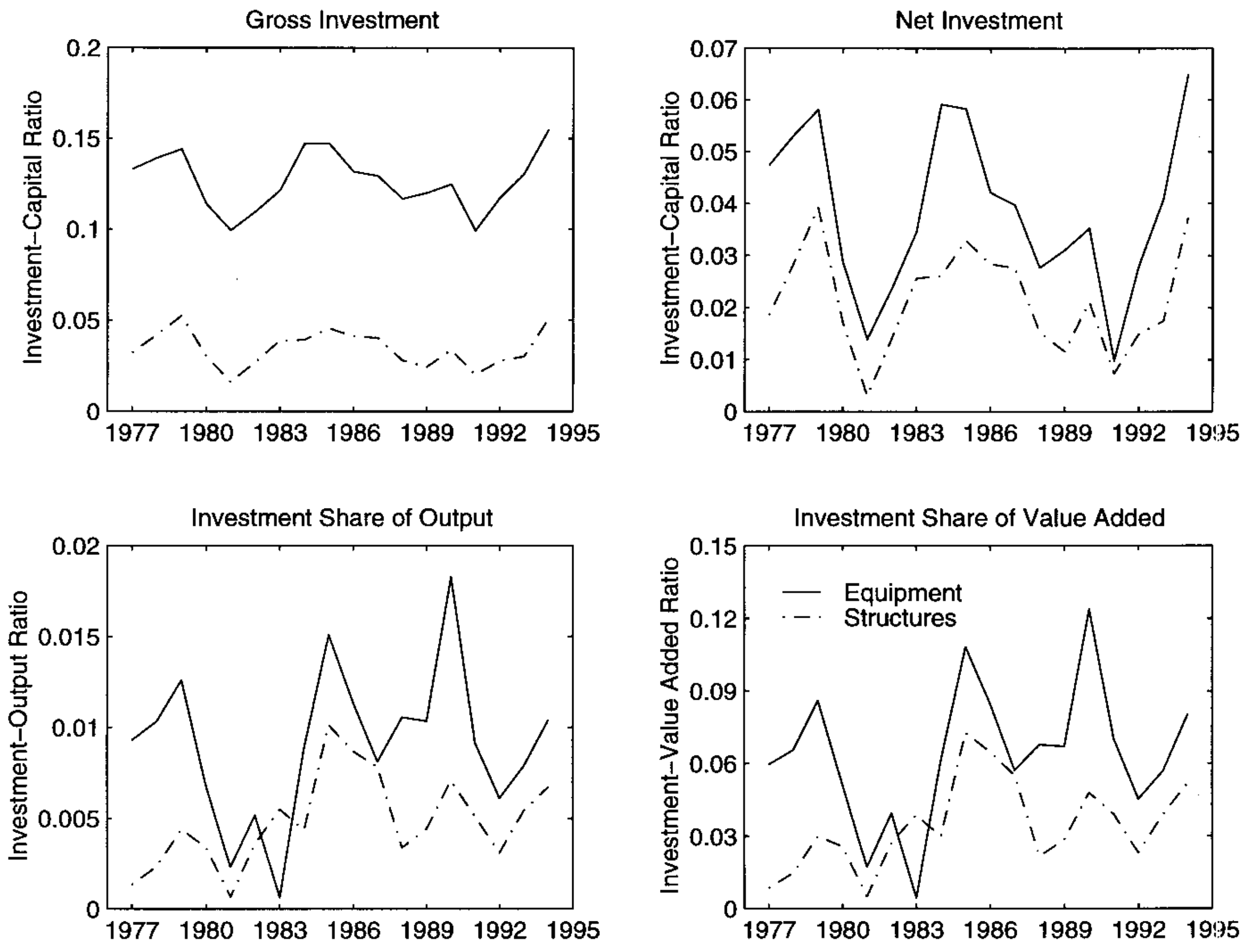

Figure 3: Characteristics of Equipment and Structures Investment

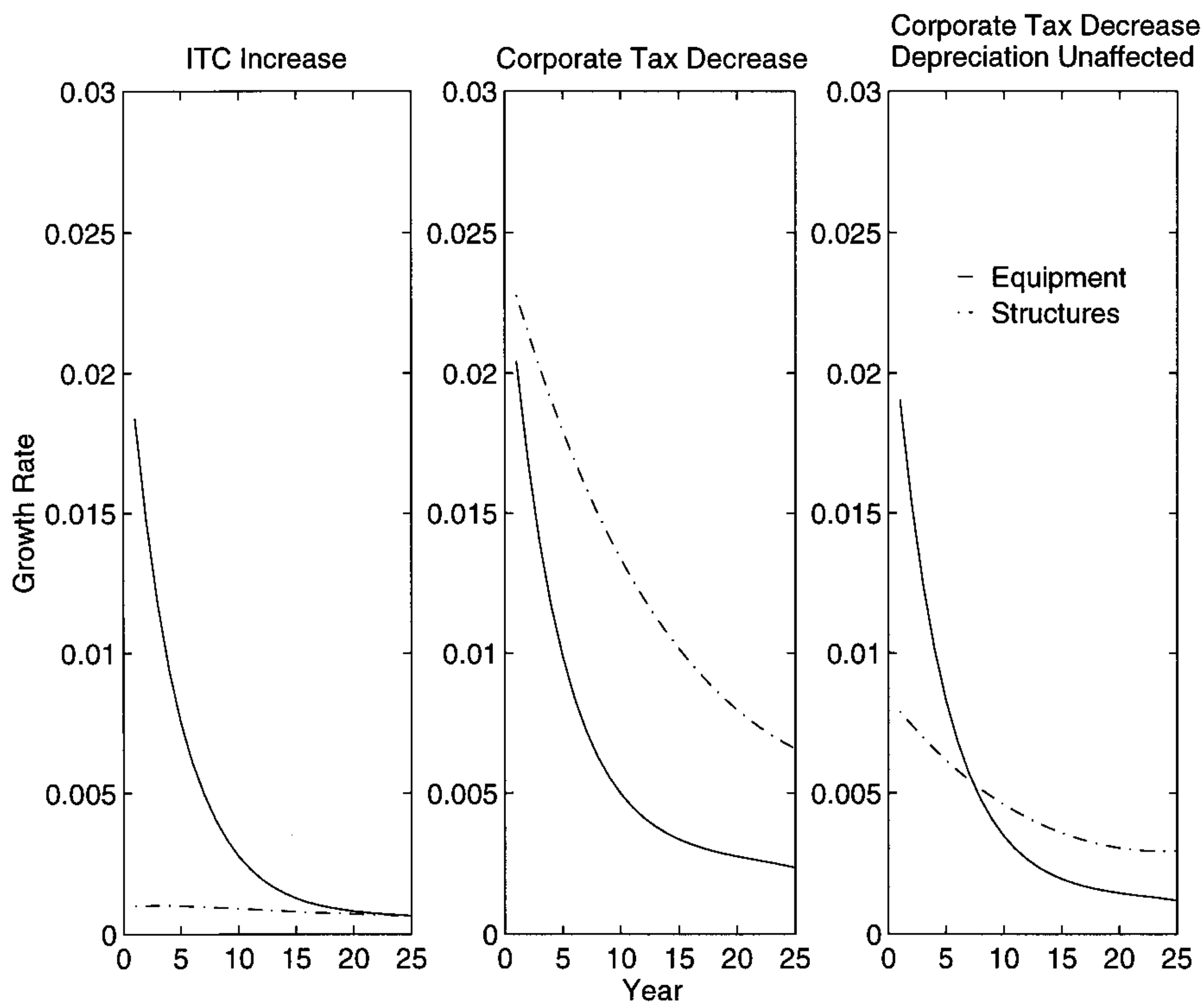

Figure 4: The Dynamic Effects of Taxation: Cobb-Douglas Production, Unrelated Adjustment Costs

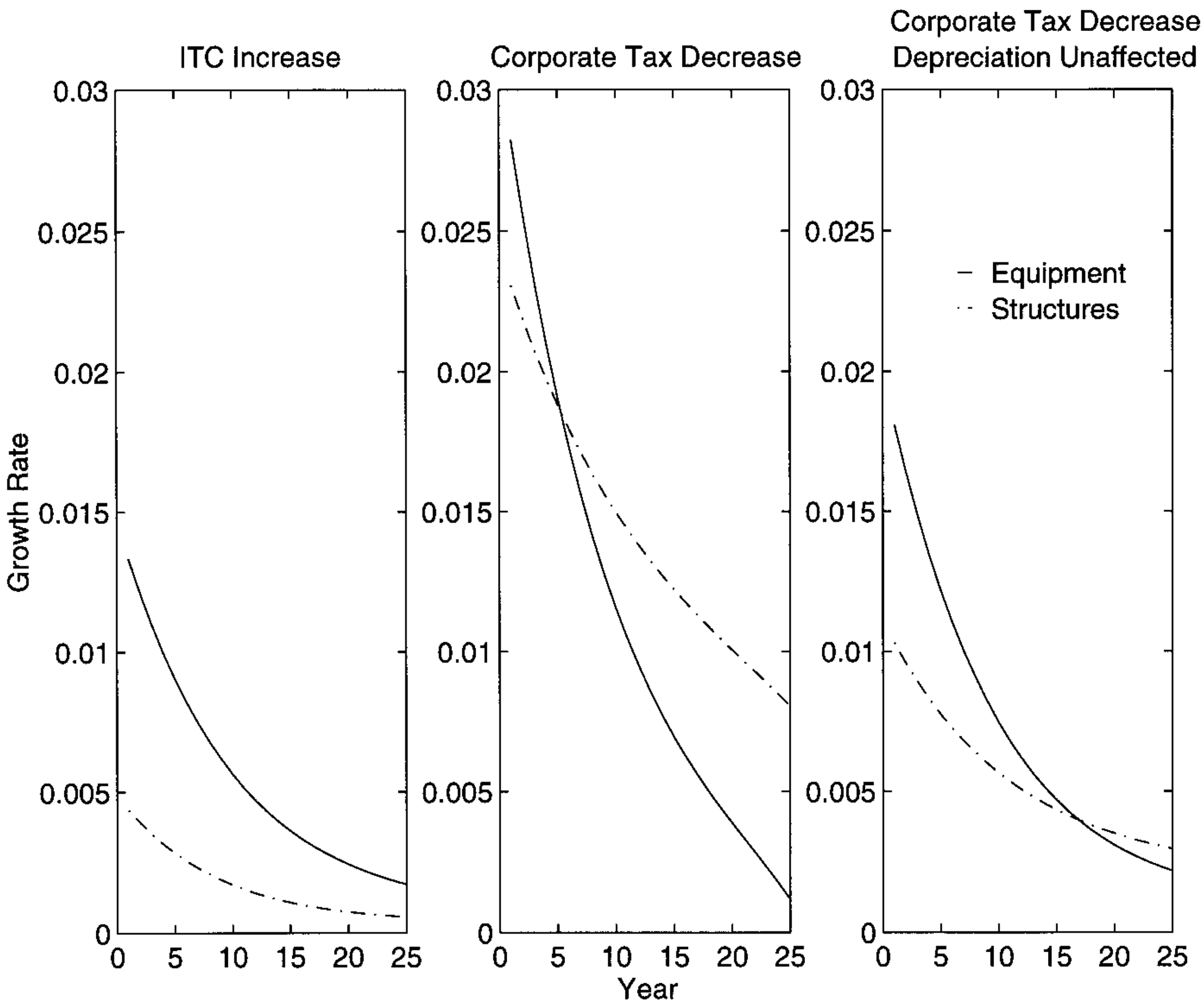

Figure 5: The Dynamic Effects of Taxation: Translog Production, Interrelated Adjustment Costs