# Non-convexities in the Adjustment of Different Capital Inputs: A Firm-level Investigation

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## Summary

Recent developments in investment research have highlighted the importance of non-convexities and irreversibilities in the firms' adjustment of quasi-fixed inputs. However, aggregation across capital goods may smooth out the discontinuities associated with the adjustment of individual assets. The lack of suitable data is one of the reasons why empirical work has strongly relied on the assumption of capital homogeneity. In this paper we exploit a new data set of 1539 Italian firms which allows us to disaggregate capital and consider separately purchases and sales of assets. We disaggregate between equipment and structures and construct measures of fundamental Q to capture investment opportunities associated with each asset. To uncover the pattern of dynamic adjustment we use non-parametric techniques to relate each individual investment to own fundamental Q.

**Keywords**: Investment, heterogenous capital, non-convexities, fundamental Q, panel data

**JEL**: D24, G31, C33, C34

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# 1 Introduction

Capital homogeneity is a critical assumption often made by static and dynamic studies on production and factor demands. The main problem is that different capital goods command different prices, display different depreciation patterns and receive different tax treatments. The possibility of combining several capital inputs into a single aggregate relies on a very restrictive assumption on the firm's technology, namely that capital inputs must be perfect substitutes. Consequently the firm can produce more output by applying either more machines or more buildings. The assumption of capital homogeneity may be considered one of the reasons why structural models of investment, such as Tobin's Q and Euler equations, perform poorly when confronted with the data (see e.g. Whited, 1994, 1998).

Only a few studies analyze investment in heterogenous capital goods. Hayashi and Inoue (1991) relate the growth rate of a scalar index of several capital inputs to Tobin's Q and test the model using Japanese panel data. However, the theoretical model rests on the hypothesis of weak separability for the capital inputs within the firm's profit function. Chirinko (1993) uses U.S. aggregate data to estimate an equation in which the specific capital investment, relative to the aggregate stock, depends on Tobin's Q and on the ratios of the other capital investments to the aggregate stock. If capital is homogenous the coefficients of these investment regressors should be the same. Capital homogeneity is rejected when the author distinguishes between equipment and structures. Cummins and Dey (2000) adopt an Euler equations approach to study investment in equipment and structures on U.S. firm-level data. They postulate a translog technology and quadratic adjustment costs. Previously, Pindyck and Rotemberg (1983) fitted two Euler equations for equipment and structures to U.S. total manufacturing data. Bond and Cummins (2000) study U.S. firm investment in tangible and intangible capital. The authors develop and estimate a single equation model where the tangible investment-capital ratio depends linearly on Tobin's Q and on the ratio between intangible investment and tangible stock. However, due to the unobservability of the stock of intangibles, they need to consider the ratio between the two stocks to be time invariant.[1] A recent paper by Bontempi,

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[1] In the case of studies on investment in fixed and R&D capital, and especially on financing constraints, a number of papers depart from the capital homogeneity assumption (see for instance Nickell and Nicolitsas, 1996, and Bond, Harhoff and Van Reenen, 1999).

Del Boca, Franzosi, Galeotti, and Rota (2001) show how differently Q models behave when estimated separately for equipment and structures. They also show a different behavior when compared to the Q model with homogeneous capital. All the above studies represent contributions to the literature sharing the assumption of quadratic adjustment costs. It is well-known that this framework implies a gradual adjustment of the actual capital stocks to their desired long-run levels.

Recent developments in investment research highlight the importance of non-convexities and irreversibilities in the adjustment of quasi-fixed inputs by individual firms: see, for instance, Dixit and Pindyck (1994), Abel and Eberly (1994, 1996), Caballero (1997), and Caballero and Engel (1999). In this stream of studies, the adjustment of the quasi-fixed inputs may or may not occur, depending on whether the marginal net benefit from investing exceeds (falls short of) a certain threshold value. Hence, the adjustment may be episodic and lumpy, rather than smooth for all the values of the marginal net benefits as implied by the traditional convex adjustment costs explanations of investment behavior. Fixed costs, irreversibilities, and other forms of non-convexities may explain why traditional models of investment do not perform empirically well. In addition, they may be important factor for understanding business cycle behavior.[2] Non-convexities alter investment dynamics both at firm and aggregate level, making optimal investment a non-linear function of its fundamentals. For the U.S., the empirical evidence on non-convexities has been growing starting from the explorative work by Doms and Dunne (1998) up to the investigation by Cooper, Haltiwanger, and Power (1999) and to the "gap methodology" approach proposed by Caballero, Engel, and Haltiwanger (1995) and Caballero and Engel (1999).[3] While these papers typically use plant level data but do not estimate structural investment equations, more recent contributions adapt Tobin's Q models to take into account non-convex costs and estimate their extent using firm-level panel data.[4] Papers in this area are those by Eberly (1997), Whited (1998), Barnett and Sakellaris (1998, 1999), and Abel and Eberly (2002). All these studies still assume that different types of capital goods can be combined

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[2] Ramey and Shapiro (1998) and Veracierto (2002) stress irreversibility or partial revesibility; Thomas (2002) and Khan and Thomas (2002) focuse instead on fixed costs.

[3] See also Nilsen and Schiantarelli (2000) on Norwegian data and Gelos and Isgut (2001a, 2001b) on Colombia and Mexico.

[4] Cooper and Haltiwanger (2000) use an indirect inference approach to estimate general adjustment cost structures on U.S. plant level data.

into a single aggregate. Even when they emphasize the importance of capital heterogeneity, they base the empirical investigation on single indexes of fixed capital (see, for instance, Eberly, 1997; Abel and Eberly, 2002; Goolsbee and Gross, 2000).[5]

Although the focus of the recent investment literature is on modelling idiosyncratic behavior, aggregation of capital inputs may also hide non-convex patterns in adjustment costs and irreversibilities. As shown in Bontempi, Del Boca, Franzosi, Galeotti and Rota (2001), aggregation may also dilute the convexities that characterize the adjustment pattern of specific capital inputs. Indeed, the authors find that the standard Q model fits the data quite well for equipment, but not for total capital (equipment plus structures) since it fails to adequately represent investment in structures.

This paper explicitly considers the possibility of non-convex adjustment costs and of a non-linear relationship between optimal investment and its determinants. It complements the previous study by Bontempi, Del Boca, Franzosi, Galeotti and Rota (2001) and focuses on the issue of capital investment under input heterogeneity. In this paper we analyze the dynamic adjustment of capital inputs by imposing as little structure as possible on its shape. The previous paper assumed quadratic costs of adjustment, thus obtaining a linear relationship between the investment rate in individual capital inputs and the corresponding marginal Q. In this paper we maintain the basic disaggregation between equipment and structures and rely on the notion of Tobin's Q to summarize investment opportunities associated with each individual capital input. However, under capital heterogeneity and in the presence of unlisted small and medium sized firms, the standard measure of Q, based on stock market valuation, cannot be used (unlike in Eberly, 1997; Whited, 1998; Barnett and Sakellaris, 1998, 1999; Abel and Eberly, 2002). To capture a firm's investment opportunities we rely on the Fundamental Q approach (FQ hereafter) suggested by Abel and Blanchard (1986) and Gilchrist and Himmelberg (1995, 1998). We construct measures of FQ for equipment and structures and then use flexible parametric techniques to study the nature of the dynamic adjustment of investment in each capital input.

The results show that the linear adjustment pattern implied by the tradi-

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[5] Abel and Eberly (2002) explicitly entertain the issue of aggregation of different capital goods and show how the Q model needs to be modified. However, adjustment costs apply separately to each type of capital but with a common coefficient.

tional quadratic adjustment cost hypothesis is not consistent with the data. We find clear evidence of non-linear behavior in the case of net investment (purchases-sales) and purchases in relation to our measure of FQ. For all the types of capital goods we consider, equipment, structures and total capital (equipment+structures), we find an initial *S-shaped* adjustment pattern followed by a linear, positively sloped portion. The case for sales is, instead, statistically weak. Our findings imply that neglecting the underlying heterogeneity in adjustment costs for different capital inputs may lead to misleading conclusions about the dynamics of investment decisions.

The paper is structured as follows. In the next section we describe the data we use in the empirical investigation. Section 3 discusses our choice of a proxy for investment opportunities based on the notion of FQ. Section 4 presents the investment relationship on which we base our investigation of firms' dynamic adjustment of capital inputs and the methods we employ. In Section 5 we discuss the empirical results. Concluding comments and directions for future research end the paper.

## 2 Data Description

We use data from Italy's Company Accounts Data Service (CADS), a large database with information on the balance sheets and income statements of more than 52,000 Italian firms covering all industries from 1982 to 1995. In addition to company accounts the database contains information on firm demographics, location, sector, type of organization, ownership status, the composition of the board of management and the board of auditors. CADS is well representative of the population of Italian companies, covering over 50% of the value added produced by the firms included in the Census of the Italian Central Statistical Office. In Appendix A.1 we report variable definition and construction.

The original dataset comprised 5,086 manufacturing firms over 1982-1995; after omitting firms with incomplete or problematic records we were left with a balanced panel of 1,539 companies for the 1985-1995 period (see Appendix A.1 for cleaning criteria).[6] This subsample remains representative of the

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[6] The main reason why we are left with 1539 firms is the need to have companies with continuous records on equipment and structure and, separately, on purchases and sales of those assets.

original dataset.[7] Consistently with the Italian industrial structure, our data mostly cover non-listed companies: in the final sample out of 1,539 units only 0.32% is listed on the stock exchange. According to the national figures, only 0.13% of Italian manufacturing companies were listed on the Stock Exchange in 1995. This is the main justification for adopting the FQ approach to model investment in Italy. Another aspect of our dataset is the inclusion of a high number of small and medium firms. These are predominant in Italy: on average the Italian manufacturing limited liability companies have 44 employees. The average number of employees in our final sample is 166 employees with 30.2% of the companies have less than 50 employees.[8]

We define net investment as purchases minus sales of fixed capital, and gross investment as purchases only; unlike gross investment, net investment may take negative values, when capital sales are larger than purchases. Table 1 presents the summary statistics for the variables we use: net investment $(I/K_T, I/K_E, I/K_S)$, gross investment or purchases $(I/K_T^+, I/K_E^+, I/K_S^+)$ and disinvestment or sales $(I/K_T^-, I/K_E^-, I/K_S^-)$, real sales $(S/K_T, S/K_E, S/K_S)$, and operating income $(\Pi/K_T, \Pi/K_E, \Pi/K_S)$. All these variables are divided by the stock of total capital $(T)$, equipment $(E)$, and structures $(S)$. The positive skewness suggests that investment is temporally concentrated; in particular, this is true for structures which exhibit a zero net investment rate in the first quartile. Purchases follow a similar pattern. Most of the disinvestment is small and have a markedly skewed distribution, with the highest degree in the case of structures. The mean annual rates of disinvestment are as low as 0.037, 0.040 and 0.035 respectively, with an even lower median, strongly affected by the high number of zero episodes. Given the high frequency of positive outliers due to the skewness of our data, we use pseudo-standard deviation which is a more robust as a measure of variability.[9]

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[7] Only firms which have been in receipt of a bank loan at the initial date are tracked. This introduces a possible specification bias through the exclusion of new and/or financially weak firms. Firm mortality is very low and is unlikely to be problematic.

[8] In Table A.2.1, in Appendix A.2, we report the distribution of firms by industry and size.

[9] The pseudo-standard deviation is defined as the ratio of the interquartile range (*q3-q1*) and 1.349 where 1.349=2*0.674 is the interval containing 50% of the cases in a normal distribution.

Table 1 Descriptive Statistics

| | $q_1$ | $Median$ | $q_3$ | $Mean$ | $Pseudo - s.dev.$ | $Skewness$ |
|---|---|---|---|---|---|---|
| $I/K_T$ | 0.066 | 0.129 | 0.228 | 0.178 | 0.120 | 3.632 |
| $I/K_E$ | 0.065 | 0.157 | 0.289 | 0.221 | 0.166 | 4.199 |
| $I/K_S$ | 0 | 0.037 | 0.181 | 0.177 | 0.134 | 4.258 |
| $I/K_T^+$ | 0.083 | 0.155 | 0.274 | 0.215 | 0.141 | 7.724 |
| $I/K_E^+$ | 0.076 | 0.168 | 0.304 | 0.261 | 0.169 | 6.723 |
| $I/K_S^+$ | 0.003 | 0.044 | 0.194 | 0.212 | 0.142 | 7.727 |
| $I/K_T^-$ | 0 | 0.002 | 0.014 | 0.037 | 0.010 | 22.601 |
| $I/K_E^-$ | 0 | 0.002 | 0.011 | 0.040 | 0.008 | 21.202 |
| $I/K_S^-$ | 0 | 0.0001 | 0.004 | 0.035 | 0.003 | 32.118 |
| $S/K_T$ | 0.095 | 0.231 | 0.353 | 0.286 | 0.191 | 2.573 |
| $S/K_E$ | 0.043 | 0.224 | 0.371 | 0.309 | 0.243 | 4.220 |
| $S/K_S$ | 0.032 | 0.186 | 0.304 | 0.251 | 0.202 | 3.482 |
| $\Pi/K_T$ | 0.022 | 0.230 | 0.354 | 0.286 | 0.246 | 3.068 |
| $\Pi/K_E$ | 0.024 | 0.225 | 0.366 | 0.309 | 0.253 | 5.949 |
| $\Pi/K_S$ | 0.012 | 0.177 | 0.304 | 0.251 | 0.216 | 4.964 |

In Table 2 we report the frequency of zero and negative net investment episodes, in order to better understand the different behavior of investment in equipment and structures and the problems that may derive from aggregation.[10] This information will turn out to be of relevance when presenting the estimation results in the next section. In the case of equipment, zero net investment episodes are markedly less frequent than positive and negative investment cases. On the contrary, structures show the highest incidence of inactivity and negative-investment episodes: 13.8% against the 0.52% of equipment and 11.77% against the 9.33% of equipment, respectively. This indicates the possibility that structures, more than equipment, are characterized by non-convex adjustment costs which affect the relationship between investment and FQ. Total net investment shows a lower incidence of zeros and negative-investment (0.43% and 2.37%, respectively) and this suggests that aggregation tends to smooth out the discontinuities which are likely to characterize structures. Recent studies show that fixed components in

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[10] Further information on zero and negative net investment episodes by industry and size is provided in Tables A.2.2-A.2.3 in Appendix A.2. Zeros in this literature are sometimes defined as all values of investment belonging to a small neighborhood of zero. Here we consider only strictly null investment rates.

the adjustment cost function and partial irreversibility are likely to affect investment behavior. If this is the case, aggregation over different capital goods fails to account for differences in adjustment costs by smoothing out the adjustment paths. However, none of these studies focus on heterogeneous capital inputs.

Table 2: Frequency of Zero and Negative Investment

| | **Aggr.** | **Equip.** | **Struc.** |
|---|---|---|---|
| **a. Frequency of I/K >0, due to:** | **97.20** | **90.15** | **74.43** |
| $I/K^+ \neq 0$ and $I/K^- = 0$ | 27.63 | 30.32 | 28.88 |
| $I/K^+ > I/K^-$, given $I/K^+ \neq 0$ and $I/K^- \neq 0$ | 69.57 | 59.83 | 45.55 |
| **b. Frequency of I/K =0, due to:** | **0.43** | **0.52** | **13.80** |
| $I/K^+ = 0$ and $I/K^- = 0$ | 0.39 | 0.48 | 13.78 |
| $I/K^+ = I/K^-$, given $I/K^+ \neq 0$ and $I/K^- \neq 0$ | 0.04 | 0.04 | 0.02 |
| **c. Frequency of I/K <0, due to:** | **2.37** | **9.33** | **11.77** |
| $I/K^+ = 0$ and $I/K^- \neq 0$ | 0.30 | 2.31 | 3.02 |
| $I/K^+ < I/K^-$, given $I/K^+ \neq 0$ and $I/K^- \neq 0$ | 2.08 | 7.02 | 8.75 |

Number of observations 16929 (1985-1995)

Net investment is the result of buying and selling: zero and negative investment may therefore hide simultaneous buying and selling of capital goods. This is confirmed by the other rows of Table 4, where net investment is disaggregated in its components. Companies buy and sell capital in the same year: for instance, total capital shows 27.63% of cases in which capital is only purchased, 0.30% of cases in which there are sales only, and 71.69% of cases in which capital is both purchased and sold (69.57%+0.04%+2.08%). It is therefore important to separately consider purchases and sales of heterogeneous capital goods. Further information may be obtained from Table 3, where we show how many observations entail a zero level of gross investment and what is the fraction of gross investment activity associated with large variations in the capital stock.[11] Structures are characterized by a much

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[11] See Doms and Dunne (1998). Following these authors Attanasio, Pacelli, and Reduto dos Reis (2000) document the occurrence of spikes and zeros in U.K. establishment level investment rates. In their descriptive work they exploit a remarkable panel dataset which contains information on separate groups of assets and on their disposal.

higher number of zeros: 16.80% of observations against 2.79% in the case of equipment. Moreover, in the case of structures, the largest gross investment episode yields 48.37% of cumulative gross investment over the 11 years period; this fraction is twice that of equipment. Thus, as in the case of net investment, aggregation over different types of capital goods tends to hide the lumpy nature of investment in structures.

Table 3: Lumpiness of Purchases and Sales

| | **Aggr.** | **Equip.** | **Struc.** |
|---|---|---|---|
| **Temporal concentration of purchases:** | | | |
| - frequency of $I/K^+ = 0$ | 0.69 | 2.79 | 16.80 |
| - contribution of the largest $I/K^+$ to cumulative $I/K^+$ over the sample period | 26.54 | 29.00 | 48.37 |
| **Temporal concentration of sales:** | | | |
| - frequency of $I/K^- = 0$ | 28.02 | 30.80 | 42.66 |
| - contribution of the largest $I/K^-$ to cumulative $I/K^-$ over the sample period | 60.63 | 65.13 | 73.88 |

The high incidence of zero sales in all types of capital goods is apparent from the table. The highest percentage of zeros, 42.66%, again occurs in structures, along with the largest sales episode in any given year (that covers 73.88% of cumulative sales over the sample period). Given the concentrated nature of sales, the standard linear relationship between disinvestment and Q is likely not to perform well empirically relative to the case of purchases. This implies that the high number of zeros should be taken explicitly into account and that the standard strictly convex adjustment cost specification may not be appropriate when we look at sales of capital goods. These are indeed the econometric findings of Bontempi, Del Boca, Franzosi, Galeotti and Rota (2001) and motivate the empirical investigation that follows.

## 3 Investment Opportunities

In the economic literature investment is prompted by comparing the desired capital stock with its actual level, or by considering how much the Tobin's Q differs from unity. In the recent literature, which emphasizes the role of non-convexities and irreversibilities, the former approach is often referred to as "gap methodology" (Caballero, Engel, and Haltiwanger, 1995, Caballero and Engel, 1999).[12] This model predicts that the firm's capital adjustment is a non-linear function of the imbalances between desired and actual capital.[13] In particular, the actual capital stock is referred to as mandated stock, while the desired stock is taken to be proportional to the frictionless stock. The frictionless capital stock, in turn, is the level of input that would hold in the absence of frictions at any time.

Eberly (1997), Barnett and Sakellaris (1998, 1999), and Abel and Eberly (2002) instead rely on the notion of Tobin's average Q. They exploit stock market data to compute the numerator of Q and rely on a number of assumptions which allow to use the average ratio *in lieu* of the theoretically relevant marginal ratio.

Our model of capital adjustment neither depends on the computation of a desired or frictionless capital stock nor on the stock market valuation required to compute average Q. The first approach is somewhat *ad hoc* since the target capital stock does not embed any consideration concerning expectations of the future forcing variables. Moreover, it requires the specification of both desired and frictionless capital stocks and the estimation of the latter is particularly problematic in a context of many capital inputs.[14]

Contrary to what is generally assumed in the literature, it can be shown that models based on average Q can also be applied to the case in which the production function is not linear homogeneous, competition in the output market is not perfect and the number of quasi-fixed inputs is greater than one (Galeotti and Schiantarelli, 1991). However, in order to be applicable, the Q model requires that the firm be quoted in the stock market, a condition not fulfilled in the present context.[15]

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[12] The flexible accelerator model can be considered as the ancestor of the "gap methodology". The difference with the modern approach lies in the rate of adjustment. Note that also Tobin's Q models can be seen as applications of the "gap methodology", in the price space rather than in the quantity space. Under certain conditions one can establish a duality between these two approaches (Galeotti, 1987).

[13] This approach is also adopted by other authors, including Goolsbee and Gross (2000), Gelos and Isgut (2001a), and Carlsson and Laséen (2001). Goolsbee and Gross (1997) study adjustment costs with data on heterogeneous capital goods, even though the results reported refer to a single capital index.

[14] In most specifications the frictionless capital depends upon output and the capital-specific user cost. The latter is typically unobserved in firm or plant-level analyses.

[15] In addition the stock market is assumed to be efficient, although the Q model can be used to study the role of non-fundamentals for investment (Galeotti and Schiantarelli,

Our proxy for investment opportunities draws on Tobin's work and follows the FQ approach proposed by Abel and Blanchard (1986) and by Gilchrist and Himmelberg (1995, 1998). Investment in individual capital goods is the outcome of a firm's intertemporal optimization in which the profit opportunities of investing in a certain capital good are compared at the margin with its cost. These opportunities are represented by the shadow price of capital or FQ, which is evaluated by means of the following auxiliary model.

Let $\beta^s (1-\delta_j)^{s-1} \equiv (\lambda_j)^s$ where $\beta$ is the firm's discount rate and $\delta_j$ the $j$-th capital good depreciation rate. Then the $i$-th firm's FQ associated with the $j$-th capital input is given by the following expression:

$$FQ_{j,it} = E\left[q_{j,it} \mid \Omega_{it}\right] = E\left[\sum_{s=1}^{\infty} \lambda_j^s \frac{\partial \Pi_{it+s}}{\partial K_{j,it+s}}\right] \mid \Omega_{it} \tag{1}$$

where $\partial\Pi/\partial K_j$ indicates the marginal profit from the $j$-th capital type. Equation 1 shows that FQ is unobserved in two respects: first, it entails an infinite sum of future values; second, the marginal profitability needs to be estimated. Following Abel and Blanchard (1986) and Gilchrist and Himmelberg (1995), the first problem is dealt with by estimating a set of Vector Auto-Regression (VAR) equations for the state variables which we presume forecast the marginal profitability of capital.[16] As to the second aspect, to construct the expectations of the future marginal profitability of capital we assume that the firm's technology is Cobb-Douglas.[17] Under perfect competition in the output market, we may relate marginal profits of capital to the observed variables as follows:

$$\frac{\partial \Pi_{it}}{\partial K_{j,it}} = \rho_{j,i}\left(\frac{\Pi_{it}}{K_{j,it}}\right) \tag{2}$$

where $\rho_{j,i}$ is the output elasticity of capital. In equation 2, marginal profitability relating to each capital input is proportional to the corresponding

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1994).

[16] See Holtz-Eakin, Newey and Rosen (1988) who extend the VAR methodology to longitudinal data.

[17] A key aspect of the construction of fundamental Q for individual capital inputs is the ability to relate marginal profitability to observed variables. These in turn form the basis of the auxiliary VAR model. Besides being widely employed in firm-level studies, the Cobb-Douglas appears to be the only technological specification fulfilling that requirement.

average profitability. Profits in this paper are proxied by operating income.[18]

Consider a vector $x_{j,it}$ comprised of capital-specific operating income to capital and sales to capital ratios and any other variables containing information which is useful for forecasting the future marginal profitability of capital. More precisely, the vector $x_{j,it}$ contains the right hand sides of 2 and **??**, i.e. the operating income-based and the sales-based marginal profitability of each capital good. Assume that $x_{j,it}$ follows a stationary stochastic process with a finite-order autoregressive representation that we write in its AR(1) companion form:

$$x_{j,it} = A_j x_{j,it-1} + f_{j,i} + d_{j,t} + u_{j,it} \tag{3}$$

where $A_j$ is the matrix of coefficients specific for each type of capital goods. Cross sectional heterogeneity is captured by a vector $f_{j,i}$ of firm unobservable fixed effects, while $d_{j,t}$ is a vector of shocks common to all firms for which we assume a finite-order autoregressive representation. Finally, $u_{j,it}$ is a vector of disturbance terms that are orthogonal to $x_{j,it-1}$. Assume that variables dated $t$ are part of the information set, i.e. $x_{j,it} \in \Omega_{it}$. Since we are assuming a stationary process and a finite-order autoregressive representation for both $x_{j,it}$ and $d_{j,t}$, then the expectation of $x_{j,it+s}$ given $x_{j,it}$ may be written as:

$$E\left[x_{j,it+s} \mid x_{j,it}\right] = A_j^s x_{j,it} \tag{4}$$

where we have omitted the terms involving $f_{j,i}$ and $d_{j,t}$ and their related parameters. Under the assumption of a one-period gestation lag, the shadow value of capital may be approximated as follows:

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[18] Following Gilchrist and Himmelberg (1998), the technology and demand parameters, $\rho_{j,it}$ and $\sigma_{j,it}$, are calculated as industry-level averages as follows:

$$\tilde{\rho}_{j,h} = \left( \frac{1}{N_h T} \sum_{i \in N_h} \sum_{t \in Tj,it} \frac{\Pi_{it}}{K_{j,it}} \right)^{-1} \frac{1}{N_h T} \sum_{i \in N_h} \sum_{t \in Tj,it} (r_{it} + \delta_{j,ht})$$

where $j$ indicates the type of capital good; $h$ denotes industry, and $N_h T$ is the number of firm-year observations in industry $h$; $\delta_{j,ht}$ is the rate of physical depreciation which varies by industry and time; $r_{it}$ is the interest rate on financial debt. Further details about variables construction are in the appendix A.1.

$$\begin{aligned}
E\left[q_{j,it} \mid \Omega_{it}\right] &= \sum_{s=1}^{\infty} \lambda_j^s E\left[\pi_{j,it+s} \mid \Omega_{it}\right] \\
&= \sum_{s=1}^{\infty} \lambda_j^s E\left[c' x_{j,it+s} \mid x_{j,it}\right] \\
&= \sum_{s=1}^{\infty} c' \lambda_j^s A_j^s x_{j,it} \\
&= c'\left(I - \lambda_j A_j\right)^{-1} \lambda_j A_j x_{j,it} \\
&= FQ_{j,it}
\end{aligned} \tag{5}$$

where, in the second row, the unobservable expected stream of marginal profit of each type of capital is substituted by the expectation of the observable firm fundamentals useful in forecasting marginal profitability; the discounted value of the expectation of $x_{j,it+s}$ given $x_{j,it}$ is the capital-specific FQ, $FQ_{j,it}$. If the hypothesis of perfect competition holds and the operating income-based marginal profitability of capital is the first element of the information set $x_{j,it}$, then $c$ is a vector with the first element equal to one and zeros elsewhere.[19] In the empirical specification which follows we assume perfect competition. As discussed earlier, expression 5 is based on the assumption of one-period gestation lag.[20] We will replace $A$ with $\widehat{A}$ obtained from estimation of VAR models for the case $j = 1, 2$, i.e. equipment and structures, as well as for the standard case of aggregate capital. We employ a GMM methodology and use first differences to eliminate the individual firm effects. We also include a vector of time dummies which capture aggregate shocks. Instruments are time dummies and lagged values (two and three lags) of operating income ($oi$) and sales ($s$), both divided by the relevant capital stock. The VAR(2) estimates are reported in Appendix A.3. We then construct three FQs, one for each type of capital good, following expression 5. The term $\lambda$ varies according to the type of capital: $\lambda = 0.8614$ for total investment, $\lambda = 0.8394$

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[19] If we assume that variables dated $t$ are not part of the information set, the formula of fundamental Q in 5 is slightly different. If we compute fundamental Q in this way, the performance of the estimated Q models is somewhat inferior but the main conclusions hold true.

[20] We have also experimented with the case of no gestation lags, which implies that today's investment becomes immediately productive. There were only qualitative differences but the one period gestation lag appeared to deliver more robust results.

for equipment and $\lambda = 0.8944$ in the case of structures.[21] The resulting series, $\widehat{FQ}_{j,it}$, are the estimated capital-specific FQs.

# 4 Investment Relationship

Consider a value-maximizing firm which uses many capital inputs. The necessary condition for an optimal choice of investment requires equating, at each point in time, the marginal cost to the marginal benefit from investing in each capital input. This condition can be represented as follows:

$$E\left[q_{j,it} \mid \Omega_t\right] = p_{j,t} + G\left(I_{j,it}, K_{j,it}, \xi_{j,it}\right) \tag{6}$$

where the left hand side represents the benefit from investing in a unit of the $j$-th capital good, while the right hand side represents the corresponding cost, given by the sum of an installation and an acquisition component.[22] In particular, $p$ is the market price of new capital goods, $I$ is investment and $K$ the corresponding stock; $\xi$ is a shock to installation costs. In view of its empirical implementation, we substitute the left hand side of equation 6 with the estimate of FQ, $\widehat{FQ}_{j,it}$, and, because we do not have firm-specific observations on prices, we use time dummies to capture price and other time-varying firm-invariant effects. Unobserved individual heterogeneity is captured by firm-specific effects. Following the literature, we assume that $G(.)$ is homogenous of degree zero in $(I, K)$. Thus, our empirical model is:

$$\frac{I_{j,it}}{K_{j,it}} = H(\widehat{FQ}_{j,it}) + \mu_{j,i} + \nu_{j,t} + \epsilon_{j,it} \tag{7}$$

The terms $\mu_{j,i}$ and $\nu_{j,t}$ represent the composite firm fixed effects and time effects resulting from the substitution of equation 5 into 6; the error $\epsilon_{j,it}$ includes both the shock to the adjustment costs, $\xi_{j,it}$, and the error introduced

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[21] These values correspond to the sample average of firm and time specific discount factors, i.e. $\widetilde{\lambda}_j = \frac{1}{H}\sum_{h\in H}\frac{1}{N_h T}\sum_{i\in N_h}\sum_{t\in T}\beta_{it}(1-\delta_{j,ht})$, where $H$ is the total number of industries. The discount rate $\beta_{it}$ is calculated as $[1+(1-\tau_t)r_{it} - z_{ht}]^{-1}$, where $\tau_t$ is the statutory tax rate on firm profits, and $z_{ht}$ is the inflation rate. We follow Abel and Blanchard (1986) and Gilchrist and Himmelberg (1995) who consider the average across firms and over time of the discount factor, arguing that any firm-specific and any year-specific effect is captured by the individual and temporal effects.

[22] In writing equation 6 we are implicitly assuming that the costs of installing capital goods of type $j$ are not affected by investment in other varieties.

by replacing the present value of future marginal profits of each type of capital goods with its proxy obtained through the VAR auxiliary forecasting model. The formulation 7 is essentially the same as those employed by Eberly (1997), Barnett and Sakellaris (1998, 1999) and Abel and Eberly (2002). The only difference is that it refers to investment in individual capital inputs and hence it depends on the own FQ rather than on the average Q.

In order to investigate potential non-convexities in the investment function it is desirable to impose as little structure as possible on the form of $H(.)$. Thus, we estimate this function in a flexible parametric fashion. In particular, we fit a spline (piecewise linear) to equation 7 (see, for instance, Suits, Mason, and Chan, 1978). An obvious non-parametric alternative is represented by kernel and local linear estimators. The problem with these methods is that they do not easily allow us to condition on other control variables, such as firm and time dummies.

While two contributions adopt a non-parametric approach, we are not aware of any study that uses splines to examine potential non-convexities in investment models. In the spirit of the "gap methodology", Goolsbee and Gross (2000) estimate kernel regressions of investment as a function of the gap using a panel of firms in the U.S. airline industry and data on heterogenous types of capital.[23] The average investment function has a flat portion for negative and low levels of mandated investment and a positively sloped linear portion as mandated investment increases. According to the authors, this finding is consistent with irreversibilities or with large costs of disinvestment, and quadratic costs conditional on positive investment. The other example is represented by Gelos and Isgut (2001a) who derive non-parametric estimates of the average adjustment function for Colombian and Mexican firms using a kernel estimator. For any mandated investment rate, the method computes a weighted average of the observed investment rates in its neighborhood, with weights given by the kernel.[24] The pictures presented by the authors do not look very different from the estimates with U.S. data obtained by Goolsbee and Gross (2000): negative mandated investment rates do not coincide with negative actual investment, suggesting irreversibilities. In the range of positive investment rates, however, the shapes of the estimated adjustment

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[23] Although this aspect does not emerge clearly from the paper, the authors do not appear to undertake separate non-parametric analyses for each capital input.

[24] Note that the authors do not control for firm and time specific effects in their kernel investment regressions. This confirms the difficulty we mentioned earlier of properly accounting for unobserved heterogeneity using large panels in kernel estimation.

functions are approximately linear. In any event, the estimated functions are clearly different from the theoretical case of quadratic adjustment costs.

# 5 Empirical Results

We estimate equation 7 for homogeneous capital, equipment and structures using splines. We consider a 4-knot linear spline obtained by calculating the value of the FQ at the two-decile points (20%, 40%, 60% and 80%). The choice about number and location of the knots is somewhat arbitrary. A reasonable way to start is to consider a limited number of knots evenly distributed across the whole range of values of Q.[25] In our case, omitting time and firm subscripts, we consider $H(.)$ linear and write it as follows:

$$H^r(FQ) = \alpha^r + \gamma^r FQ \qquad r = 1, ..., 5 \tag{8}$$

where, indicating the knot by $k$, we have that $k^r \leq FQ \leq k^{r+1}$, $k^1 = 0$ and $k^6 = \infty$. The condition specifying the knots is

$$\alpha^{r+1} = \alpha^r + \gamma^r k^r - \gamma^{r+1} k^{r+1} \qquad r = 1, ...4 \tag{9}$$

Note that if the $\gamma^r$ are all equal we obtain the basic linear investment-FQ relationship. We use linear splines because they are more easily interpretable relative to higher-order approximations. The estimation of the linear spline is performed using GMM applied to a reparametrized model which solves in the knot restrictions. We use first differences to eliminate the individual effects which are likely to be correlated with the lagged values of investment rates.[26]

We begin by considering the case of net investment, that is purchases less sales. The first step is to ask whether the 4-knot specification is adequate for the data or if further simplification is warranted. Hence, for each type of capital we test a 4-knot spline specification against a 2-knot case and a simple linear regression of investment on the own FQ. Of course, the last case corresponds to the traditional quadratic adjustment costs specification.

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[25] The functions $H^r(FQ)$ in equation 7 may be defined to be linear, quadratic, or of some higher order. In our case consider them linear.

[26] Instruments are lagged values of operating income and sales, appropriately divided into the five ranges representing the spline, and a set of dummies defining the ranges of the spline.

In Table 4 we report the values of the test computed on the basis of the minimized objective functions (see Newey and West, 1987, and Bond, Bowsher and Windmeijer, 2001).[27] The 2-knot spline is computed by maintaining the first and the last segment of the 4-knot spline and by collapsing the other segments corresponding to the two-decile points 40%, 60% and 80%, to a single one. This allows us to test whether the two extreme sections play an important role in determining the shape of the spline. Moreover, the three specifications are nested within each other. In each of the three columns, simplifications of the 4-knot spline specification are rejected. However, in the case of structures, the result is ambiguous in the sense that, had we confined attention solely to the linear and 2-knot specifications, we would have been unable to reject linearity. This leaves us with a suspicion that the 4-knot spline specification for structures may be over-parameterized.

Table 4: J-test Results - Net Investment

| | **Total** | **Equipment** | **Structures** |
|---|---|---|---|
| | 1 | 2 | 3 |
| Linear model vs 4-knot: $\chi^2_4$ | 32.0<br>(0.00%) | 25.5<br>(0.00%) | 11.1<br>(2.55%) |
| 2-knot vs 4-knot spline: $\chi^2_2$ | 6.60<br>(3.69%) | 13.8<br>(0.10%) | 8.2<br>(1.66%) |
| Linear model vs 2-knot spline: $\chi^2_2$ | 25.4<br>(0.00%) | 11.7<br>(0.29%) | 2.90<br>(23.46%) |

Note: rejection frequencies in parentheses

Figure 1 illustrates the splines in the case of net investment (purchases-sales) for total investment, equipment and structures respectively.[28] We plot-

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[27] This test is a likelihood ratio test equivalent for GMM and is given by the expression:

$$D_{RU} = N\left(J\left(\widetilde{\theta}_2\right) - J\left(\widehat{\theta}_2\right)\right)$$

where $J(.)$ is a model's minimized objective function, $\widehat{\theta}_2$ is the two-step GMM estimator in the unrestricted model and $\widetilde{\theta}_2$ is the two-step GMM estimator in the restricted model. Under the null hypothesis that the restrictions are valid, $\mathrm{D}_{RU}$ has an asymptotic $\chi^2$ distribution with $r$ degrees of freedom.

[28] Estimates of the spline regression model are reported in Appendix A.4. If we look at the specification tests in Tables A.4.1-A.4.3, we generally find support for our procedure. The only dubious cases are given by the Sargan tests for overidentifying restrictions in

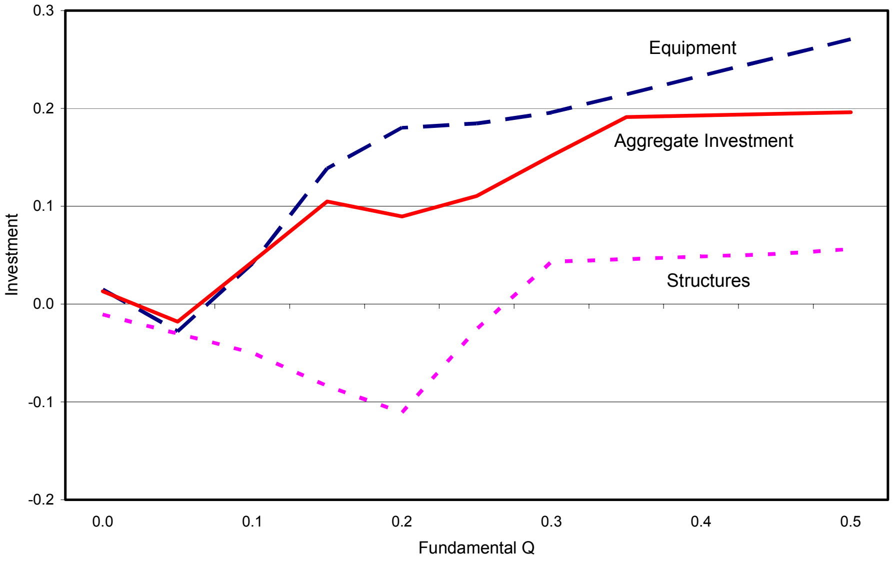

Figure 1: Net Investment: Purchases - Sales

ted the spline with respect to value of FQ between 0.0 and 0.5, since, as shown in Figures 4-6 below, this is the range with the highest frequency of firms.

In the figure net investment is characterized by the following pattern: for values of the FQ ranging between 0.0 and 0.4 net investment in equipment, structures and total capital displays a $S$-shape. For values larger than 0.4 the relationship between investment and FQ is linear, in particular it is positively sloped for equipment and structures, but it is almost flat for total capital. Before drawing any conclusion, however, we need to analyze the behavior of purchases and sales separately.

Beginning with purchases of capital goods, in Table 5 the test for aggregate investment indicates that the 2-knot specification is the preferred specification. The test rejects linearity and shows that there is no gain in

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the net investment equation in the case of structures (column 3 in Table A.4.1), and more decisively the test for second order serial correlation for the net investment equation relating to total capital (column 1 in Table A.4.1). Turning to the estimated parameters, these are generally not significant in all the equations relating to sales (Table A.4.3), while the opposite happens in the case of net investment (Table A.4.1) and purchases (Table A.4.2). We find that structures perform less well than aggregate and equipment investments.

considering a 4-knot spline. In the case of equipment, instead, the test fails to reject the 4-knot spline specification, while, when we consider structures, we find that linearity cannot be rejected. Thus, in the case of purchases, the linearity characterizing the equation for structures is smoothing the spikiness we associated with the equipment equation, making the 2-knot specification an acceptable approximation for aggregate investment.

Table 5: J-test Results - Purchases of Capital

| | **Aggregate** | **Equipment** | **Structures** |
|---|---|---|---|
| | 1 | 2 | 3 |
| Linear model vs. 4-knot spline: $\chi^2_4$ | 40.85<br>(0.00%) | 32.40<br>(0.00%) | 6.90<br>(14.13%) |
| 2-knot spline vs. 4-knot spline: $\chi^2_2$ | 1.77<br>(77.76%) | 18.40<br>(0.01%) | 4.60<br>(10.03%) |
| Linear model vs. 2-knot spline: $\chi^2_2$ | 39.07<br>(0.00%) | 14.00<br>(0.09%) | 2.30<br>(31.66%) |

Note: rejection frequencies in parentheses

When we consider purchases of capital goods we find a pattern similar to that of net investment. Indeed, in Figure 2, which shows the 4-knot spline for aggregate capital, equipment and structures respectively, we find an initial $S$-shape followed by a positively sloped linear pattern in all three cases.

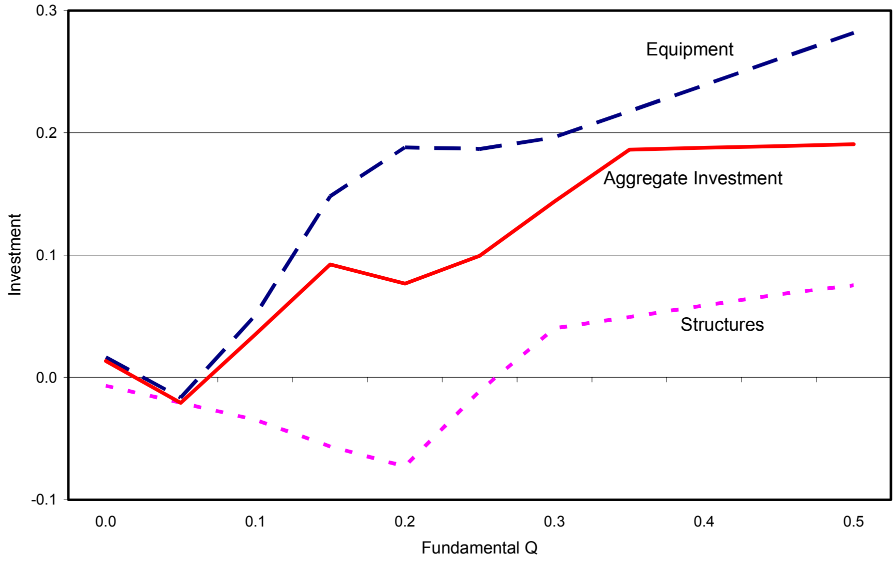

Figure 2: Purchases of Capital

Consider now the case of sales of capital. In Table 6 we present the tests of the spline specifications. Despite the lack of precision in the estimates, the first two columns of the table suggest that the 4-knot spline specification is preferred. The same result appears to hold also for structures. However, as in the corresponding case reported in Table 5, the test fails to reject linearity relative to the 2-knot spline suggesting possible over-parameterization.

Table 6: J-test Results - Sales of Capital

| | **Aggregate** | **Equipment** | **Structures** |
|---|---|---|---|
| | 1 | 2 | 3 |
| Linear model vs. 4-knot spline: $\chi^2_4$ | 13.80<br>(0.00%) | 36.30<br>(0.00%) | 14.50<br>(0.59%) |
| 2 knot spline vs. 4-knot spline: $\chi^2_2$ | 8.00<br>(1.83%) | 7.50<br>(2.35%) | 14.20<br>(0.08%) |
| Linear model vs. 2-knot spline: $\chi^2_2$ | 5.80<br>(5.50%) | 28.80<br>(0.00%) | 0.30<br>(86.07%) |

Note: rejection frequencies in parentheses

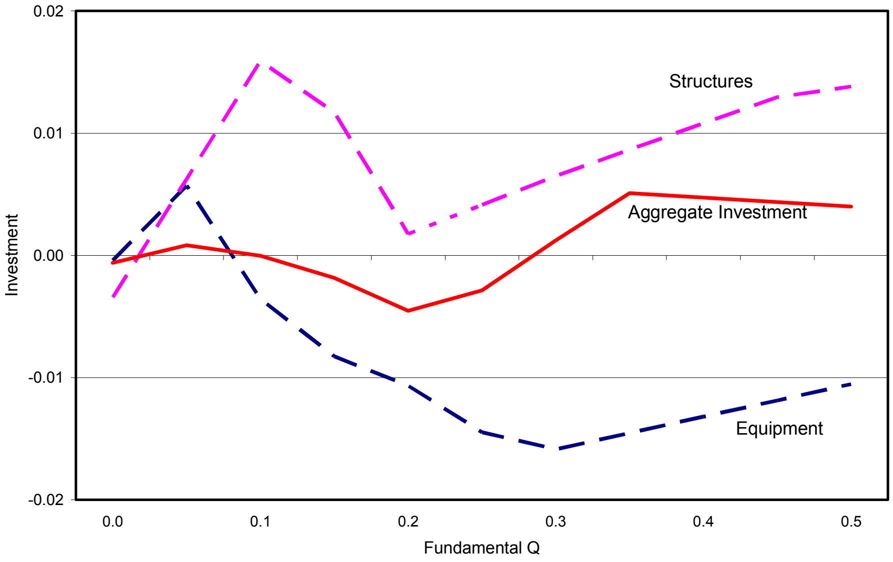

Figure 3: Sales of Capital

Sales of aggregate capital, equipment and structures are represented in Figure 3.

Although we report the graphs for all the types of capital, the underlying estimated coefficients are not well-determined. The apparently highly non-linear behavior in the case of aggregate investment and structures is the consequence of lack of precision in the estimates. Interpreting this evidence in terms of the pattern of a firm's dynamic adjustment, therefore, appears of limited usefulness.

A very interesting exercise is represented by the following figures which show the distribution of the firms along the spline.[29] In Figure 4 we present the case of aggregate investment (equipment plus structures) distinguishing between purchases, sales, and net investment. The graph shows that the highest percentage of firms is included in the region of values of the FQ ranging between 0 and 0.4.[30] This suggests that, in the case of net investment

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[29] There is no specific reason why the horizontal axis in these and the previous figures is limited to a value of Q equal to one. As figures 4-6 show, nearly all observations fall in that range.

[30] We also estimated the model over the range of FQ between 0.0 and 0.4. The pattern

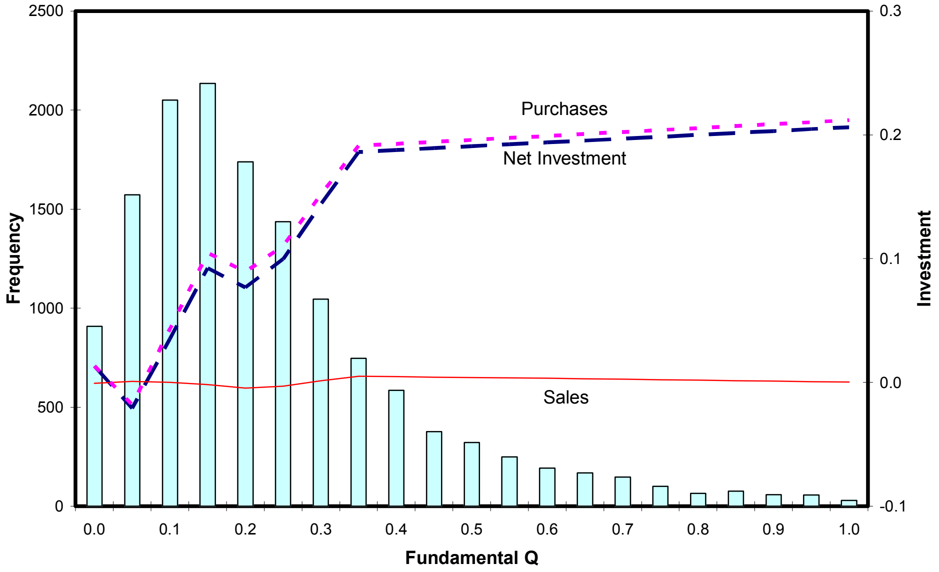

Figure 4: Firms' Distribution and 4-knot Spline - Aggregate Capital

(purchases minus sales) and purchases, aggregate investment is typically nonlinear. For the sake of completeness, we have also represented in the graph sales of aggregate capital, although, as explained earlier, the lack of precision in the estimates does not allow us to draw interesting conclusions.

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of investment does not significantly change from that shown in Figures 1-6. This indicates robustness of the results discussed above.

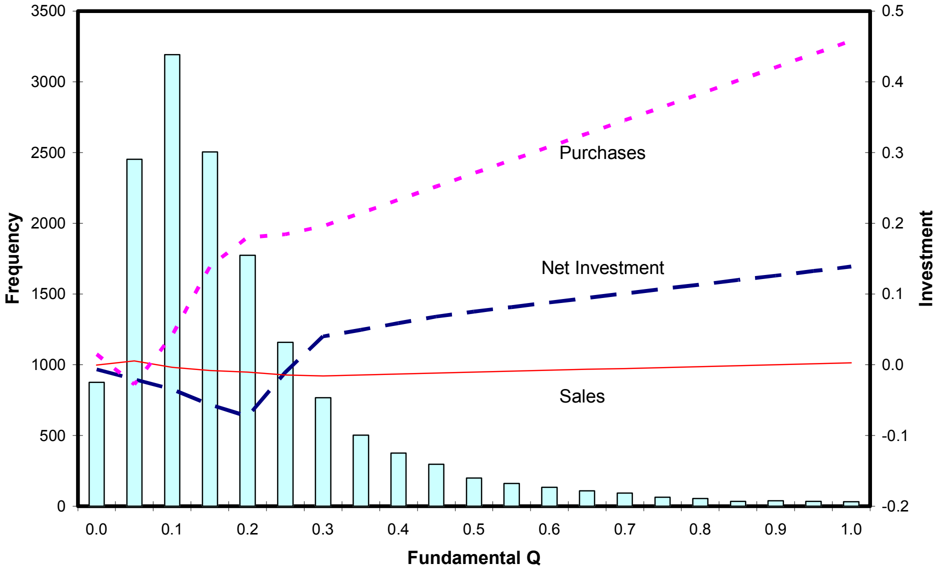

Figure 5: Firms' Distribution and 4-knot Spline - Equipment

In Figure 5 we describe the behavior of investment in equipment and maintain the distinction between purchases, sales, and net investment. The values of the FQ which describe the investment opportunities of the majority of the firms in our sample range between 0 and 0.3. The graph indicates that, in the case of equipment, net investment and purchases typically follow an S-shaped pattern. As in the previous graph, the lack of precision in the estimates of sales does not allow us to draw definitive conclusions on the pattern of dismissal of equipment.

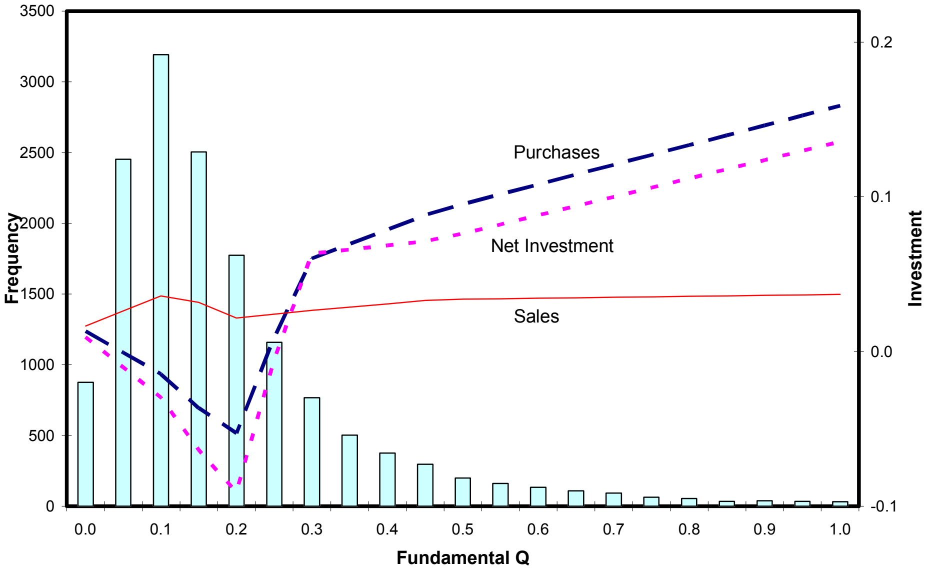

Figure 6: Firms' Distribution and 4-knot Spline - Structures

Finally, in Figure 6 we represent the 4-knot model in the case of structures. In the range of the FQ between 0 and 0.3, while sales remain largely unidentified, we observe that purchases and net investment are characterized by a non-linear pattern.

The graphical representation of the spline estimation allows us to draw the following conclusions. 1) In order to understand investment behavior it is not only very important to consider heterogeneous capital but also it is essential to distinguish between purchases and sales. 2) The dynamic adjustment of capital goods is typically non-linear. 3) If we restrict our attention to the case of purchases of capital and net investment (the pattern of the latter is dominated by purchases), we find that for an initial range of values of the FQ between 0.0 and 0.4, the dynamic adjustment follows an $S$-shape. This implies that investment is much more responsive to (very) low values of Q and becomes less reactive to higher values of Q. 4) The linear portion of the adjustment, which would be consistent with the traditional hypothesis of quadratic adjustment costs, is an acceptable representation for only a small number of firms. 5) The underlying estimated coefficients for sales of capital goods are not well-determined. The apparently highly non-linear behavior in the case of aggregate investment and structures is the consequence of lack of precision in the estimates.

How do the above findings compare to those of other papers? Our initial $S$-shape region is consistent with the "convex for low Qs, concave for high Qs" pattern of Barnett and Sakellaris (1998). Interestingly, these authors consider purchases well as net investment. They adopt the Tobin's average Q methodology and estimate their model using U.S. data.[31] Our findings can also be comparable to those in Abel and Eberly (2002) who, as in the work by Barnett and Sakellaris, consider the U.S. case and the stock market-based average Q. In their homogeneous capital case, looking at purchases, the authors find a decreasing response of investment to high values of Q.[32] They also find a statistically weak relationship between sales of capital and the Tobin's Q, in a Tobit framework. Our results are also similar to those by Goolsbee and Gross (2000) who consider the U.S. airline industry and by Gelos and Isgut (2001), who analyze Colombian and Mexican plant-level data. Both studies adopt the gap methodology. They find that investment adjustment is characterized by an initial flat region followed, when investment becomes positive, by a positive linear portion consistent with quadratic costs of adjustment. Also in their case, therefore, linearity throughout the model is rejected. Our results are also consistent with those of Whited (1998) who fits an Euler equation for (aggregate) investment after positing a fourth-order polynomial adjustment cost function. Although this specification improves the performance of the model slightly, the linear specification is decisively rejected. Finally, Cooper and Haltiwanger (2000) consider a comprehensive formulation of adjustment costs, comprised of a convex component, a concave one, of transaction costs, and of partial or full irreversibility. The authors find that a model mixing both convex and concave adjustment costs together with irreversibility fits the data best.[33]

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[31] Barnett and Sakellaris (1998) use a technically more sophisticated approach than ours, which allows for endogenous thresholds or investment regimes. This complexity represents, however, the reason why the authors do not take into account the possibility of endogeneity of Q.

[32] Abel and Eberly (2002) obtain this results by estimating a parametric investment-Q relationship wich exploits an isoelastic specification of the adjustment cost function. This choice prevents the authors from obtaining $S$-shaped dynamic adjustment patterns.

[33] It should be apparent that the approach in this paper is not suited for investigating fixed costs of adjustment. However, very recent evidence, also form labor economics, appears to point to the empirical importance of irreversibilites relative to fixed costs (Ramey and Shapiro, 2001; Kramarz and Michaud, 2002).

# 6 Conclusions

Much of the investment literature is based on the assumption of quadratic adjustment costs which implies linearity in the dynamic adjustment of the firm's capital inputs. Recent research on investment highlights the importance and the role of non-convexities and irreversibilities in capital inputs where the adjustment may be episodic and lumpy, and, as a consequence, be related non-linearly to fundamentals.

Several papers have attempted to validate these new approaches empirically. However, these investigations have all been based on the hypothesis of capital homogeneity and use data on a single aggregate capital input. Aggregation may hide non-convex patterns in adjustment costs and irreversibilities and smooth out the discontinuities of the individual adjustment of various capital inputs.

In this paper we have explicitly considered non-linear dynamic adjustment patterns for heterogeneous capital: our capital input is disaggregated in equipment and structures. We rely on the notion of Fundamental Q to summarize investment opportunities associated with each individual capital input. Specifically, we use spline functions to study the nature of the dynamic adjustment of investment in each capital input.

Our results confirm that the linear adjustment pattern implied by the quadratic adjustment cost assumption is generally contradicted. In particular, we find clear evidence of non-linear behavior in the case of purchases of different capital goods. Firms show an $S$-shaped pattern for purchases of capital goods and net investment in relation to our measure of Fundamental Q. Our findings are in line with the evidence found in recent studies of corporate investment decisions in which patterns of aggregate investment may be very different from those in individual capital assets. This result is very important because it shows that, by focusing only on the aggregate, we may reach misleading conclusions about the importance of adjustment costs, since this hides the underlying heterogeneity in adjustment costs for different capital inputs.

# References

Abel, A.B. and O.J. Blanchard (1986), "The Present Value of Profits and Cyclical Movements in Investment", *Econometrica*, 54, 249-273.

Abel, A.B. and J.C. Eberly (1994), "A Unified Model of Investment Under Uncertainty", *American Economic Review*, 84, 1369-1384.

Abel, A.B. and J.C. Eberly (1996), "Optimal Investment with Costly Reversibility", *Review of Economic Studies*, 63, 581-593.

Abel, A.B. and J.C. Eberly (2002), "Investment and $q$ with Fixed Costs: An Empirical Analysis", University of Pennsylvania, mimeo, revised.

Attanasio, O.P., L. Pacelli, and I. Reduto dos Reis (2000), Aggregate Implications of Plant Level Investment Behaviour: Evidence from the U.K.ARD", mimeo.

Barnett, S.A. and P. Sakellaris (1998), "Non-Linear Response of Firm Investment to Q: Testing a Model of Convex and Non-Convex Adjustment Costs", *Journal of Monetary Economics*, 42, 261-288.

Barnett, S.A. and P. Sakellaris (1999), "A New Look at Firm Market Value, Investment, and Adjustment Costs", *Review of Economics and Statistics*, 81, 250-260.

Bond, S., C. Bowsher, and F. Windmeijer (2001), "Criterion-based Inference for GMM in Autoregressive Panel-data Models", *Economics Letters*, 73, 379-388.

Bond, S.R., D. Harhoff, and J. Van Reenen (1999), "Investment, R&D and Financial Constraints in Britain and Germany", Institute for Fiscal Studies Working Paper N.99/5.

Bond, S.R.. and J.G. Cummins (2000), "The Stock Market and Investment in the New Economy: Some Tangible Facts and Intangible Fictions", *Brookings Papers on Economic Activity*, 1, 61-108.

Bontempi, M.E., A.Del Boca, A. Franzosi, M. Galeotti, and P.Rota (2001), "Capital Heterogeneity: Does It Matter? Fundamental Q and Investment on a Panel of Italian Firms", Fondazione Eni Enrico Mattei Working paper N.88.01 (revised September 2002).

Caballero, R.J. and E.M.R.A. Engel (1999), "Explaining Investment Dynamics in U.S. Manufacturing: A Generalized (S,s) Approach", *Econometrica*, 67, 783-826.

Caballero, R.J. (1997), "Aggregate Investment", National Bureau of Economic Research Working Paper N.6264, forthcoming in J.B. Taylor and M. Woodford (eds.), *Handbook of Macroeconomics*, Amsterdam: North-Holland.

Caballero, R.J., E.M.R.A. Engel, and J.C. Haltiwanger (1995), "Plant-Level Adjustment and Aggregate Investment Dynamics", *Brookings Papers on Economic Activity*, 2, 1-39.
Carlsson, M. and S. Laséen (2001), "Capital Adjustment Patterns in Swedish Manufacturing Firms: What Model Do They Suggest?", mimeo, Department of Economics, Uppsala University.
Chirinko, R.S. (1993), "Investment, Tobin's $Q$, and Multiple Capital Inputs", *Journal of Economic Dynamics and Control*, 17, 907-928.
Cooper, R. and J. Haltiwanger (2000), "On the Nature of Capital Adjustment Costs", National Bureau of Economic Research Working Paper No.7925.
Cooper, R., J. Haltiwanger and L. Power (1999), "Machine Replacement and the Business Cycle: Lumps and Bumps", *American Economic Review,* 89, 921-946.
Cummins, J.G. and M. Dey (2000), "Taxation, Investment, and Firm Growth with Heterogenous Capital", mimeo.
Davidson, R. and J.G. MacKinnon (1993), *Estimation and Inference in Econometrics*, Oxford: Oxford University Press, 1993.
Dixit, A.K. and R.S. Pindyck (1994), Investment under Uncertainty, Princeton: Princeton University Press.
Doms, M., and T. Dunne (1998), "Capital Adjustment Patterns in Manufacturing Plants", *Review of Economic Dynamics,* 1, 409-429.
Eberly, J.C. (1997), "International Evidence on Investment and Fundamentals", *European Economic Review*, 41, 1055-1078.
Galeotti, M. (1987), "On the Dual Relationship between Flexible Accelerator and Q Theories of Investment: A Note", *Rivista Internazionale di Scienze Economiche e Commerciali*, XXXIV, 771-776.
Galeotti, M. and F.Schiantarelli (1991), "Generalized $Q$ Models of Investment", *Review of Economics and Statistics*, 73, 383-392.
Galeotti, M. and F.Schiantarelli (1994), "Stock Market Volatility and Investment: Do Only Fundamentals Matter?", *Economica*, 61, 147-165.
Gelos, R.G. and A. Isgut (2001a), "Irreversibilities in Fixed Capital Adjustment. Evidence from Mexican and Colombian Plants", *Economics Letters*, 74, 85-89.
Gelos, R.G. and A. Isgut (2001b), "Fixed Capital Adjustment: Is Latin America Different?", *Review of Economics and Statitistics*, 83, 716-726.
Gilchrist, S. and C. Himmelberg (1995), "Evidence on the Role of Cash Flow for Investment", *Journal of Monetary Economics*, 36, 541-572.

Gilchrist, S. and C.P. Himmelberg (1998), "Investment, Fundamentals and Finance", in B.S. Bernanke and J.J. Rotemberg eds., *NBER Macroeconomics Annual*, Cambridge: MIT Press, 223-274.

Goolsbee, A. and D.B. Gross (2000), "Estimating Adjustment Costs with Data on Heterogenous Capital Goods", National Bureau of Economic Research Working Paper No.6342, Revised.

Hayashi, F. and T. Inoue (1991), "The Relation between Firm Growth and $Q$ with Mutiple Capital Goods: Theory and Evidence from Panel Data on Japanese Firms", *Econometrica*, 59, 731-753.

Holtz-Eakin, D., W. Newey, and S. Rosen (1988), "Estimating Vector Autoregressions with Panel Data", *Econometrica, 56,* 1371-1395.

Khan, A. and J.K. Thomas (2002), "Nonconvex Factor Adjustments in Equilibrium Business Cycle Models: Do nonlinearities Matter?", Federal Reserve Bank of Minneapolis Staff Report No.306.

Kramarz, F. and M.L. Michaud (2002), "The Shape of Hiring and Separation Costs: Concave but not Fixed", paper presented at the Econometric Society European Meeting, Venice, August 25-28.

Newey, W.K. and K.D. West (1987), "Hypothesis Testing with Efficient Method of Moments Estimation", *International Economic Review*, 28, 777-787.

Nickell, S. and D. Nicolitsas (1996), "Does Innovation Encourage Investment in Fixed Capital?", LSE Centre for Economic Performance Discussion Paper N.309.

Nilsen, Ø.I., and F. Schiantarelli (2000), "Zeroes and Lumps in Investment: Empirical Evidence on Irreversibilities and Non-convexities", Department of Economics Working paper No. 337, Boston College, Revised.

Pindyck, R.S. and J.J. Rotemberg (1983), "Dynamic Factor Demands under Rational Expectations", *Scandinavian Journal of Economics*, 85, 223-238.

Ramey, V.A. and M.D. Shapiro (1998), "Costly Capital Reallocation and the Effects of Government Spending", *Carnegie-Rochester Conference Series on Public Policy*, 48, 145-194.

Ramey, V.A. and M.D. Shapiro (2001), "Displaced Capital: A Study of Aerospace Plant Closings", *Journal of Political Economy*, 109, 958-992.

Suits, D.B., A. Mason, and L. Chan (1978), "Spline Functions Fitted by Standard Regression Methods", *Review of Economics and Statistics, 60, 132-139.*

Thomas, J.K. (2002), "Is Lumpy Investment Relevant for the Business Cycle?", Federal Reserve Bank of Minneapolis Staff Report No.302.

Veracierto, M.L. (2002), "Plant-level Irreversible Investment and Equilibrium Business Cycles", *American Economic Review*, 92, 181-197.
Whited, T.M. (1994), "Problems with Identifying Adjustment Costs from Regressions of Investment on $q$", *Economics Letters*,46, 339-344.
Whited, T.M. (1998), "Why, and to What Extent, Do Investment Euler Equations Fail?", *Journal of Business and Economic Statistics*, 16, 479-488.

# A Appendix

## A.1 Variable Construction and Cleaning Criteria

- **Aggregate variables**

$\delta_T$, $\delta_E$, $\delta_S$: depreciation rates of total fixed assets, equipment and structures by year and 2-digit manufacturing industry (source: ISTAT, Italian Statistical Office ).

$p_T, p_E, p_S$: price indexes for investment in total assets, equipment and structures by year and 2-digit manufacturing industry (1995=1), (source: ISTAT).

$pp$: output price index for the 13 sub-sectors of the manufacturing industry. This price index is normalized to unity for 1995, (source: ISTAT).

$z$: output price rate of inflation for the 13 sub-sectors of the manufacturing industry (1995=1), (source: ISTAT).

$\tau$: statutory corporate tax rate on firm profits, equal to 46.368% in 1985-1990; 47.826% in 1991, 52.2% in 1992-1994; and 53.2% in 1995.

- **Firm-specific variables**

$r$: actual interest rate on financial debt, computed as interest expenses on bank loans, factoring and leasing divided by the corresponding stock of debt.

$\widetilde{K}_T$,$\widetilde{K}_E$, $\widetilde{K}_S$: end of period book values of gross total fixed assets, equipment (which includes plant+machinery+equipment), and structures (which include land+buildings), respectively. Total fixed assets are equal to the sum of plant, machinery, equipment, land and buildings.

$N\widetilde{K}_T, N\widetilde{K}_E, N\widetilde{K}_S$: end of period book values of net total fixed assets, equipment and structures. For period 1991-95, the book values of both gross and net capital goods are available in the dataset. For period 1982-1990, we only have book values of gross equipment and structures; the disaggregated book values of net capital goods are obtained by subtracting the corresponding share of book value of accumulated depreciation.

$I_T^+, I_E^+, I_S^+$: capital expenditures on total fixed assets, equipment and structures. This measure includes only direct purchases of new fixed assets and it does not include fixed assets acquired through takeovers and acquisitions.

$I_T^-, I_E^-, I_S^-$: sales of total fixed assets, equipment and structures. These variables measure the sale value, and not the historical cost, i.e. it amounts to the remaining book value of sold assets (acquisition minus the book value of accumulated depreciation of assets that are sold or dismissed during the year) plus the difference between the historical acquisition cost and the market price of the sale.

Given that we only have total purchases and sales, we use the method proposed by Bond and Meghir (1994) in order to disaggregate investment and disinvestment.[34] We use the change in gross fixed assets to estimate purchases and sales of equipment and structures according to:

$$I_{E,it}^+ = I_{T,it}^+ \frac{\widetilde{K}_{E,it} - \widetilde{K}_{E,it-1}}{\widetilde{K}_{T,it} - \widetilde{K}_{T,it-1}}$$

where $E$ indicates equipment, subscript $T$ refers to total investment or capital, $i$ indicates firms, and $t$ and $t-1$ are time subscripts.

Gross investment in structures is obtained by the difference:

$$I_{S,it}^+ = I_{T,it}^+ - I_{E,it}^+$$

The same procedure applies to the case of sales, $I_{E,it}^-$ and $I_{S,it}^-$.

$I_T, I_E, I_S$: net investment in total fixed assets, equipment and structures. Net investment is computed as the difference between direct purchases, $I_{j,it}^+$, $j = T, E, S$, and sales, $I_{j,it}^-$, $j = T, E, S$, of capital goods.

$K_T, K_E, K_S$: replacement cost values of total fixed assets, equipment and structures. These values are estimated from historic cost accounts by using an iterative perpetual inventory formula, modified in order to take into account the " *Visentini Law*", which allowed firms to revalue the book values of their capital stock in 1982 and 1983. Thus, to obtain starting values for the iterative procedure we adopt the following rule:

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[34] Bond, S., and C. Meghir (1994), “Dynamic Investment Models and the Firm’s Financial Policy.”, *Review of Economic Studies*, 61, 197-222.

1. we assume that the replacement cost values are equal to the historic cost values in 1982 if firms chose to revalue in 1982 or if they did not revalue at all.

2. otherwise we consider 1983 the starting year if companies revalue their capital stock in 1983.

The use of the revalued historic cost allows us to only drop the first two years for estimation purposes, whereas it is standard in the literature to drop the first three years. The iterative perpetual inventory formula used to calculate the replacement cost value of each type of capital is the following:

$$K_{j,it+1} = K_{j,it}\left(1 - \delta_{j,ht+1}\right)\left(p_{j,ht+1}/p_{j,ht}\right) + I_{j,it+1}$$

where $j = T, E$ and $S$, $h$ indicates industry, and the initial $K_j$ is equal to the net book value of capital good $j$ in 1982 or 1983.

Investment and capital stocks are all expressed at constant prices using the relevant price indices $p_{j,ht}/p_{j,ht+1}$.

$S_T, S_E, S_S$: real sales as a proxy for the nominal value of output deflated by the output price index, *pp*, disaggregated at 2-digit industry level.

$\Pi_T, \Pi_E, \Pi_S$: operating income as a proxy for marginal product of capital, deflated by the output price index, *pp*, disaggregated at 2-digit industry level. Operating income is defined as: income before depreciation allowances, financial and extraordinary items, discontinued operations, taxes, and preference dividends.

Variables $I_T, I_E, I_S, S_T, S_E, S_S, \Pi_T, \Pi_E, \Pi_S$ are all divided by the stock at replacement cost of the relevant capital good one-period lagged.

- **Cleaning Criteria**

The original sample is a balanced panel of 5,086 manufaturing limited liability companies for the period 1982-1995. The final dataset we obtain after cleaning the data is a balanced panel of 1,539 manufacturing companies for period 1985-1995.[35] Our trimming rules were the following:

1. We eliminate firms with missing data on: aggregated and disaggregated capital stock at the beginning of the sample period, sales, and operating income. This eliminates 37.30% of the firms.

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[35] The loss of the first three years is due to the replacement value formula for capital stock and to the construction of the rate of investment based on capital lagged one period.

2. Firms with negative replacement values of the capital stock are also eliminated since they are generated when net investment is greater than lagged capital stock as a consequence of large sales of capital goods. This criterion implies an additional loss of 23.43% of companies.

3. In order to minimize measurement errors we only consider: investment rates between -1% and 5%; ratio of real output to capital between 20% and 150%; operative earnings between -50% and 75% of sales; marginal productivity of capital between -27% and 127.5%. These final criteria cuts 9% of companies. Elimination of strong outliers is necessary for disaggregating investment. Our procedure uses changes in gross capital stocks: these include not only investment but also mergers, acquisitions, divestitures, selloffs and other miscellaneous transactions.

## A.2 Data Description By Firm and Size

Table A.2.1 Distribution of Firms by Industry and Size

| **Industry** | **No. of firms** | **Frequency** |
|---|---|---|
| Food, drinks and tobacco | 167 | 10.85 |
| Textile and clothing | 177 | 11.5 |
| Leather and footwear | 31 | 2.01 |
| Timber and wooden furniture | 34 | 2.21 |
| Paper and printing | 82 | 5.33 |
| Oil, chemicals and fibres | 128 | 8.32 |
| Rubber and plastic | 101 | 6.56 |
| Minerals | 116 | 7.54 |
| Metal and metal goods | 108 | 7.02 |
| Mechanical engineering | 384 | 24.95 |
| Electric materials and precision instrum. | 93 | 6.04 |
| Motor vehicles and other transport equip. | 36 | 2.34 |
| Other manufacturing | 82 | 5.33 |
| **Size** | | |
| 0-49 | 454 | 29.71 |
| 50-259 | 875 | 57.26 |
| ≥250 | 199 | 13.02 |

## A.3 Bivariate VAR Estimation

Estimation is in first differences. Instruments are time dummies and lagged values (two and three lags) of operating income (*oi*) and sales (*s*). Time dummies are not reported; standard errors in parentheses; single and double asterisks denote 5% and 1% level of significance respectively. The Sargan test is a test of the model overidentifying restrictions. AR(1) and AR(2) are tests of first-order and second-order serial correlation in the differenced residuals. Estimation period: 1987-1995.

Table A.3.1 Bivariate VAR: Operating income

| **Variables** | **Coefficients** | | |
|---|---|---|---|
| | **(1)**<br>**Aggregate** | **(2)**<br>**Equipment** | **(3)**<br>**Structures** |
| $oi(-1)$ | $0.691^{**}$ | $0.588^{**}$ | $0.654^{**}$ |
| | (0.040) | (0.057) | (0.064) |
| $oi(-2)$ | -0.029 | -0.055 | -0.020 |
| | (0.023) | (0.041) | (0.0387 |
| $s(-1)$ | 0.018 | -0.071 | 0.101 |
| | (0.048) | (0.076) | (0.079) |
| $s(-2)$ | $-0.104^{*}$ | 0.006 | -0.081 |
| | (0.038) | (0.055) | (0.069) |
| **no. of observations** | 12312 | 12132 | 12312 |
| **Sargan** $\chi^2$ | 31.32 | $48.35^{**}$ | 40.51 |
| **AR(1)** | $-12.87^{**}$ | $-5.51^{**}$ | $-7.39^{**}$ |
| **AR(2) N(0,1)** | 0.40 | 0.18 | 1.03 |

Table A.3.2 Bivariate VAR: Sales

| **Variables** | **Coefficients** | | |
|---|---|---|---|
| | **(1)** **Aggregate** | **(2)** **Equipment** | **(3)** **Structures** |
| $oi(-1)$ | 0.016 | -0.008 | -0.013 |
| | (0.022) | (0.037) | (0.033) |
| $oi(-2)$ | -0.001 | -0.021 | 0.009 |
| | (0.015) | (0.034) | (0.025) |
| $s(-1)$ | $0.816^{**}$ | $0.636^{**}$ | $0.824^{**}$ |
| | (0.043) | (0.081) | (0.058) |
| $s(-2)$ | $-0.133^{**}$ | -0.064 | -0.059 |
| | (0.032) | (0.057) | (0.047) |
| **no. of observations** | 12312 | 12132 | 12312 |
| **Sargan** $\chi^2$ | 50.89 | $60.66^{**}$ | $46.38^{*}$ |
| **AR(1) N(0,1)** | $-8.46^{**}$ | $-6.48^{**}$ | $-7.35^{**}$ |
| **AR(2) N(0,1)** | -0.24 | 0.86 | 0.98 |

## A.4 Spline Regression Estimation

Table A.4.1: Net Investment

| Net Investment: | **Aggregate** | **Equipment** | **Structures** |
|---|---|---|---|
| $\gamma^1$ | -0.628$^{**}$ | -0.853 | -0.390 |
| | (0.259) | (0.670) | (1.013) |
| $\gamma^2$ | 1.739$^{**}$ | 2.402$^{**}$ | -0.828 |
| | (0.446) | (1.116) | (0.930) |
| $\gamma^3$ | -0.307 | 1.774 | 1.711$^{**}$ |
| | (0.447) | (0.983) | (0.681) |
| $\gamma^3$ | 0.825$^{**}$ | 0.087 | 0.332 |
| | (0.255) | (0.535) | (0.332) |
| $\gamma^3$ | 0.032 | 0.374$^{**}$ | 0.118 |
| | (0.050) | (0.107) | (0.013) |
| **no. of observations** | 13851 | 13851 | 13851 |
| **Sargan test** $\chi^2_{220}$ | 249.6 | 197.5 | 271.1$^{*}$ |
| **AR(1) N(0,1)** | -13.52$^{**}$ | -13.50$^{**}$ | -15.38$^{**}$ |
| **AR(2) N(0,1)** | -5.142$^{**}$ | 0.8247 | 1.151 |

Table A.4.2: Purchases

| Purchases: | **Aggregate** | **Equipment** | **Structures** |
|---|---|---|---|
| $\gamma^1$ | -0.685$^{**}$ | -0.658 | -0.278 |
| | (0.270) | (0.688) | (1.042) |
| $\gamma^2$ | 1.623$^{**}$ | 2.252$^{**}$ | -0.522 |
| | (0.522) | (1.106) | (1.01) |
| $\gamma^3$ | -0.312 | 1.839$^{*}$ | 1.236 |
| | (0.516) | (0.928) | (0.748) |
| $\gamma^4$ | 0.885$^{**}$ | -0.024 | 0.186 |
| | (0.284) | (0.505) | (0.350) |
| $\gamma^5$ | 0.031 | 0.427$^{**}$ | 0.127 |
| | (0.047) | (0.109) | (0.088) |
| **no. of observations** | 13851 | 13851 | 13851 |
| **Sargan test** $\chi^2_{220}$ | 240.6 | 182.8 | 271.0 |
| **AR(1) N(0,1)** | -6.191$^{**}$ | -9.546$^{**}$ | -7.540$^{**}$ |
| **AR(2) N(0,1)** | -1.709 | 0.777 | 0.898 |

Tabel A.4.3: Sales

| Sales: | **Aggregate** | **Equipment** | **Structures** |
|---|---|---|---|
| $\gamma^1$ | 0.029 | 0.122 | 0.193 |
| | (0.057) | (0.244) | (0.247) |
| $\gamma^2$ | -0.030 | -0.325 | -0.230 |
| | (0.181) | (0.276) | (0.278) |
| $\gamma^3$ | -0.053 | -0.011 | 0.047 |
| | (0.152) | (0.199) | (0.197) |
| $\gamma^4$ | 0.081 | -0.076 | 0.043 |
| | (0.067) | (0.113) | (0.069) |
| $\gamma^5$ | -0.007 | 0.026 | 0.006 |
| | (0.008) | (0.019) | (0.012) |
| **no. of observations** | 13851 | 13851 | 13851 |
| **Sargan test** $\chi^2_{220}$ | 176.9 | 160.9 | 187.4 |
| **AR(1) N(0,1)** | $-3.435^{**}$ | $-4.234^{**}$ | $-2.801^{**}$ |
| **AR(2) N(0,1)** | 0.144 | -0.291 | 1.019 |