Firm-Specific Capital, Nominal Rigidities and the Business Cycle*

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Abstract

This paper formulates and estimates a three-shock US business cycle model. The estimated model accounts for roughly 75 percent of the cyclical variation in output and is consistent with the observed inertia in inflation. This is true even though firms in the model only reoptimize their prices on average once every 1.6 quarters. The key model feature underlying this result is that capital is firm-specific. If instead we adopt the standard assumption that capital is homogeneous and traded in economy-wide rental markets, we find that firms reoptimize their prices on average once every 6 quarters. We argue that the micro implications of the model strongly favors the firm-specific capital specification.

JEL: E3, E4, E5

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1. Introduction

A key issue confronting macro economists is an apparent conflict between macroeconomic and microeconomic data. The macroeconomic data suggest that inflation is inertial. That is, inflation is slow to respond to shocks. However, the microeconomic data indicate that firms change prices frequently. This suggests that prices respond quickly to shocks. The conflict is obvious in recent macroeconomic models, which account for the inertia fact by simply assuming that firms change their prices infrequently. This account seems inconsistent with the evidence in Bils and Klenow (2002) and Golosov and Lucas (2003) and Klenow and Kryvtsov (2004) who argue that firms change prices on average more frequently than once every two quarters.

A standard approach to resolving the micro/macro conflict is to suppose that while firms do change prices frequently, they do not change them by much because marginal costs change slowly in response to shocks. From this perspective, the key task is to identify those features of the environment that make marginal cost inertial (see Ball and Romer (1990)). A problem with this approach is that it fails to come to grips with a basic fact: inflation and traditional measures of marginal cost are at best weakly correlated.[1] To be consistent with this fact, standard sticky price models imply that firms reoptimize prices much less frequently than is suggested by the micro data. For example, Gali and Gertler (1999) and Eichenbaum and Fisher (2004) find that standard Calvo pricing models imply that firms reoptimize prices roughly once every six quarters.[2] The tension between the micro and macro evidence is palpable.[3]

This paper resolves the micro/macro conflict by modifying the production technology in standard sticky price models. Our modification reduces a firm's incentive to change its price in the wake of an economy-wide shock to marginal cost. To motivate our modification, recall that standard business cycle models assume (i) a firm's production function is a linear homogeneous function of capital and labor; (ii) both factors of production can be costlessly and instantaneously transferred across firms; and (iii) the services of these factors are traded in competitive, economy-wide markets. These assumptions imply that an individual firm's

[1] However, see Sbordone (2002) who argues that at low frequencies, marginal cost and inflation do exhibit a significant correlation.

[2] Smets and Wouters' (2003) estimated model implies that firms reoptimize prices on average once every *nine* quarters.

[3] One potential way to reconcile this tension builds on the fact that the micro data only indicates how often firms actually change prices. They do not tell us how often firms reoptimize. In Calvo-style sticky price model like the one studied below, firms change prices all the time (the price changes are optimal only occasionally). So, from this point of view, the puzzle is turned on its head: sticky price models imply that firms change prices more frequently than what is suggested by the micro data. Consistent with Bils and Klenow (2002) and others, we interpret the micro evidence on the frequency of price changes as corresponding to the frequency with which firms in our model reoptimize prices.

marginal cost is independent of its own level of output. Assumptions (ii) and (iii) are empirically unrealistic.[4] In practice, they are defended on the grounds of analytic tractability.

In this paper, we abandon the simplifying assumption about capital. Instead, we assume that capital is firm-specific and that a firm can only change its capital stock over time by varying its rate of investment. This modification implies that a firm's marginal cost depends positively on its own level of output. This dependence has important implications for the firm's pricing decision in response to an exogenous shift in its marginal cost function. Straightforward manipulation of standard demand, marginal cost and marginal revenue curves confirms the following: a firm raises its price by less in response to a given shift up in its marginal cost, if its cost curve depends positively on output. The fundamental logic is simple. A firm that contemplates raising its price understands that this implies less demand and therefore less output. The reduced output implies a lower level of marginal costs. Other things the same, lower marginal costs induce profit maximizing firms to post a lower price. Thus, increasing marginal costs act as a countervailing influence on firms' incentives to raise price. This is why it is that aggregate inflation responds less to a given aggregate marginal cost shock when capital is firm-specific.[5] This logic suggests that anything (including firm-specificity of some other factor of production) which causes firms' marginal cost to be an increasing function of its output will work in the same direction as firm-specificity of capital. This is important to note because, as an empirical proposition, our analysis of firm-specific capital probably goes too far by assuming that specificity is complete.

In our analysis, we consider two versions of the model analyzed by Christiano, Eichenbaum and Evans (2004) (CEE): in one, capital is homogeneous and in the other, it is firm-specific. CEE only allow for shocks to monetary policy. To have a richer description of the data and a fuller analysis of business cycles, we modify that model to also allow for neutral and capital-embodied technology shocks.[6]

We begin by characterizing the relationship between the two versions of our model. First, among the log-linearized equations characterizing equilibrium, the only difference lies in the equation relating inflation to marginal costs. Second, the form of this equation is identical in both cases: inflation at t is equal to discounted expected inflation at $t+1$ plus a reduced form coefficient, γ, multiplying time t economy-wide average real marginal cost. Third, the difference between the two versions of the model lies in the mapping between the structural

[4] See, for example, Ramey and Shapiro (2001), who present evidence that suggests it is costly to transfer capital across firms.

[5] Since completing this research, we have learned of work by de Walque, Smets and Wouters (2004) - done independently and simultaneously - which reaches similar conclusions about the importance of firm-specific capital.

[6] See also DiCecio (2004) for a multisectoral general equilibrium model which allows for the same three shocks that we consider. Also, Edge (2004) considers a general equilibrium model with two types of technology shocks.

parameters and γ. In the homogeneous capital model, γ depends only on agents' discount rate and on the frequency, ξ_p, with which firms re-optimize prices. In the firm-specific capital model, γ is a function of a broader set of the structural parameters. For example, other things equal, the more elastic is the firm's demand curve and the more costly it is for the firm to vary capital utilization, the smaller is γ. The intuition for these results is a simple extension of the intuition discussed above.[7] Fourth, the only way that ξ_p enters into the reduced form of the model is via its impact on γ. So, if we parameterize the two versions of the model in terms of γ rather than ξ_p, they have identical implications for all aggregate quantities and prices. This observational equivalence result implies that we can estimate the model in terms of γ without taking a stand on whether capital is firm-specific or homogeneous.

Our observational equivalence implies that we cannot assess the relative plausibility of the homogeneous and firm-specific capital models using macro data. But, the two models do have very different implications for micro data. We focus on the mean time between price reoptimization, and the dynamic response to aggregate shocks of the cross - firm distribution of production and prices. These implications depend on the parameters of the model, which we estimate.

Our empirical strategy follows CEE in choosing model parameter values to minimize the differences between the dynamic response to shocks in the model and the analog objects estimated using a 10 variable vector autoregression (VAR). To compute VAR-based impulse response functions, we use identification assumptions satisfied by our economic model. That model implies: (i) the only shocks which affect productivity in the long run are innovations to neutral and capital-embodied technology; (ii) the only shock that affects the price of investment goods in the long run is the innovation to capital-embodied technology;[8] and (iii) monetary policy shocks satisfy a particular orthogonality condition. Our estimated VAR implies that the three identified shocks account for roughly seventy five percent of cyclical fluctuations in aggregate output and other aggregate quantities.

The quality of our estimation strategy depends on the ability of identified VARs to generate reliable estimates of the dynamic response of economic variables to shocks. The literature reports several examples in which VAR methods for estimating dynamic response functions are inaccurate.[9] We use Monte Carlo simulation methods to assess the reliability of VAR

[7] The more costly it is for a firm to vary its utilization of capital, the steeper is its marginal cost curve. The steeper is the marginal cost curve, the less is the firms incentive to raise its price in response to a given upward shift in marginal cost, as discussed above. The more elastic the firm's demand is, the greater the reduction in quantity demanded in response to a given rise in price. This in turn implies a greater fall in output and, hence, a greater fall in marginal cost. As noted above, the greater fall in marginal cost reduces the firm's incentive to raise its price.

[8] Our strategy for identifying technology shocks follows Fisher (2004).

[9] See, for example, Chari, Kehoe and McGrattan (2004), Cooley and Dwyer (1998), and Erceg, Guerrieri and Gust (2003).

methods in our application. For this, we generate artificial data using our estimated equilibrium model. Because the model has only three shocks, to estimate our 10-variable VAR in artificial data, we must introduce additional sources of variation. How these disturbances are selected is important for determining the outcome of the Monte Carlo simulations.[10] Our estimated VAR provides a natural estimate of this source of variation. We find that, in terms of bias and sampling uncertainty, the Monte Carlo performance of our VAR-based estimates of impulse response functions is very good.

Recall that at the estimation stage we do not need to distinguish between the homogeneous and firm-specific capital versions of the model. In terms of model fit, we find that the estimated model does a good job of accounting for the estimated response of the economy to both monetary policy and technology shocks. Interestingly, the model implies that technology shocks affect macroeconomic variables very much as a student of real business cycle theory might anticipate. Positive neutral or capital-embodied technology shocks drive output, investment, consumption and employment up. But according to the model, the reason the economy responds to technology shocks the way it does has to do with monetary policy. Our empirical results indicate that monetary policy accommodates positive shocks to neutral and capital technology. According to our equilibrium model, in the absence monetary accommodation: (i) output and hours would fall in the wake of a positive neutral technology shock; and (ii) output and hours worked would rise by much less than they actually do after a positive capital embodied technology shock. These findings are consistent with the ones reported in Gali, Lopez-Salido, and Valles (2002).

We now discuss the key properties of our point estimates. First, we find that households re-optimize wages on average once every 3.6 quarters. This is consistent with the findings in CEE. Second, our point estimate of γ is 0.035. This implies that a temporary 1% rise in nominal marginal cost produces a 0.034 percent rise in the current, aggregate price level. In the homogeneous capital version of the model, this value of γ implies that firms change prices on average once every 6 quarters. But in the firm specific capital model, this same value of γ implies that firms change price on average once every 1.6 quarters, a value that is consistent with the evidence from the micro literature.

The two versions of the model also differ sharply in terms their implications for the cross-sectional distribution of production. In the homogeneous capital model, a small percent of firms produce a very large fraction of the economy's output in the periods after a monetary policy shock. This is not the case for the firm-specific capital version of the model.

The large differences in the micro implications of the homogeneous and firm-specific

[10] For example, the analysis in Erceg, Guerrieri and Gust (2003) suggests that if the shocks excluded from the model analysis have persistent (though not exactly permanent) effects on labor productivity, VAR methods will in small samples tend to confound the effects of these with the effects of our neutral and capital-embodied technology shocks.

capital models depend on the estimated values of the structural parameters. In this regard, the key parameters are those that control a firm's elasticity of demand and the cost of varying capital utilization. According to our estimates, firms are close to perfect competitors in goods markets and it is quite costly to vary the rate of capital utilization.

In sum, the firm-specific model does a good job of accounting for the 10 macro variables that we consider. Significantly, it does so in a way that resolves the macro/micro conflict that motivates this paper.

The plan of the paper is as follows. Section 2 describes our model economy. Section 3 describes our VAR-based estimation procedure, which involves estimating the response of the economy to shocks using VAR methods, and then fitting our dynamic general equilibrium model to the impulse responses. Section 4 presents our VAR-based impulse response functions and their properties. Sections 5 and 6 presents and analyzes the results of estimating our model. Section 7 discusses the implications of our model for the cross-firm distribution of prices and production in the wake of a monetary policy shock. Section 8 discusses the accuracy of our VAR based estimator of impulse response functions, in artificial data generated by our model. Finally, Section 9 concludes.

2. The Model Economy

In this section we describe two variants of our model economy. The two variants differ according to the treatment of capital. In the *homogeneous capital model*, capital is homogeneous and can be costlessly and instantaneously reallocated among firms. This view of capital is the one adopted in the bulk of the business cycle literature. In the *firm-specific capital model* capital cannot be reallocated across firms after it has been installed. Here, the firm's beginning of period stock of capital is a state variable. That stock can only be changed over time by varying the rate of investment. The potential importance of firm-specificity of capital for business cycle fluctuations has recently been explored by Sbordone (2002), Woodford (2003, 2004), Sveen and Weinke (2004), Christiano (2004) and Eichenbaum and Fisher (2004).

For convenience, our exposition begins in terms of the homogeneous capital model. We then discuss the modifications required to allow for firm specificity in capital.

2.1. The Homogeneous Capital Model

The model economy is populated by goods-producing firms, households and the government.

2.1.1. Final Good Firms

At time t, a final consumption good, Y_t, is produced by a perfectly competitive, representative firm. The firm produces the final good by combining a continuum of intermediate goods, indexed by $i \in [0,1]$, using the technology

$$Y_t = \left[\int_0^1 y_t(i)^{\frac{1}{\lambda_f}} di \right]^{\lambda_f}, \tag{2.1}$$

where $1 \leq \lambda_f < \infty$ and $y_t(i)$ denotes the time t input of intermediate good i. The firm takes its output price, P_t, and its input prices, $P_t(i)$, as given and beyond its control. The first order necessary condition for profit maximization is:

$$\left(\frac{P_t}{P_t(i)} \right)^{\frac{\lambda_f}{\lambda_f - 1}} = \frac{y_t(i)}{Y_t}. \tag{2.2}$$

Integrating (2.2) and imposing (2.1), we obtain the following relationship between the price of the final good and the price of the intermediate good:

$$P_t = \left[\int_0^1 P_t(i)^{\frac{1}{1-\lambda_f}} di \right]^{(1-\lambda_f)}. \tag{2.3}$$

2.1.2. Intermediate Good Firms

Intermediate good $i \in (0,1)$ is produced by a monopolist using the following technology:

$$y_t(i) = \begin{cases} K_t(i)^{\alpha} \left(z_t h_t(i) \right)^{1-\alpha} - \phi z_t^* & \text{if } K_t(i)^{\alpha} \left(z_t h_t(i) \right)^{1-\alpha} \geq \phi z_t^* \\ 0 & \text{otherwise} \end{cases} \tag{2.4}$$

where $0 < \alpha < 1$. Here, $h_t(i)$ and $K_t(i)$ denote time t labor and capital services used to produce the i^{th} intermediate good. The variable, z_t, represents a time t shock to the technology for producing intermediate output. We refer to z_t as a neutral technology shock and denote its growth rate, z_t / z_{t-1}, by μ_{zt}. The non-negative scalar, ϕ, parameterizes fixed costs of production. The variable, z_t^*, is given by

$$z_t^* = \Upsilon_t^{\frac{\alpha}{1-\alpha}} z_t, \tag{2.5}$$

where Υ_t represents a time t shock to capital embodied technology (see below for further discussion). The structure of the firm's fixed cost in (2.5) is chosen to ensure that nonstochastic steady state is characterized by a balanced growth path. We denote the growth rate of z_t^* and Υ_t by $\mu_{z_t^*}$ and μ_{Υ_t} respectively, so that

$$\mu_{z^*t} = \left(\mu_{\Upsilon t} \right)^{\frac{\alpha}{1-\alpha}} \mu_{zt} \tag{2.6}$$

Throughout, we rule out entry and exit into the production of intermediate good i.

Let $\hat{\mu}_{z,t}$ denote $(\mu_{z,t} - \mu_z)/\mu_z$, where μ_z is the growth rate of $\mu_{z,t}$ in non-stochastic steady state. Throughout, we define all variables with a hat in an analogous manner. We assume that $\hat{\mu}_{z,t}$ evolves according

$$\hat{\mu}_{z,t} = \rho_{\mu_z} \hat{\mu}_{z,t-1} + \varepsilon_{\mu_z,t} \tag{2.7}$$

where $|\rho_{\mu_Z}| < 1$ and $\varepsilon_{\mu_Z,t}$ is uncorrelated over time and with all other shocks in the model. We denote the standard deviation of $\varepsilon_{\mu_Z,t}$ by σ_{μ_z}. Similarly, we assume

$$\hat{\mu}_{\Upsilon,t} = \rho_{\mu_\Upsilon}\hat{\mu}_{\Upsilon,t-1} + \varepsilon_{\mu_\Upsilon,t}, \tag{2.8}$$

where $\varepsilon_{\mu_\Upsilon,t}$ has the same properties as $\varepsilon_{\mu_z,t}$. We denote the standard deviation of $\varepsilon_{\mu_Z,t}$ by σ_{μ_Υ}.

Intermediate good firms rent capital and labor in perfectly competitive factor markets. Profits are distributed to households at the end of each time period. Let $P_t r_t^k$ and $P_t w_t$ denote the nominal rental rate on capital services and the wage rate, respectively. We assume that the firm must borrow the wage bill in advance at the gross interest rate, R_t.

Firms set prices according to a variant of the mechanism spelled out in Calvo (1983). In each period, a firm faces a constant probability, $1 - \xi_p$, of being able to re-optimize its nominal price. The ability to re-optimize prices is independent across firms and time. As in CEE (2004), we assume that a firm which cannot reoptimize its price sets $P_t(i)$ according to:

$$P_t(i) = \pi_{t-1}P_{t-1}(i). \tag{2.9}$$

Here, π_t denotes aggregate inflation, P_t/P_{t-1}.

The firm's objective function is:

$$E_t \sum_{j=0}^{\infty} \beta^j \upsilon_{t+j} \left[P_{t+j}(i) y_{t+j}(i) - P_{t+j}\left(w_{t+j} R_{t+j} h_{t+j}(i) + r_{t+j}^k K_{t+j}(i) \right) \right], \tag{2.10}$$

where E_t is the expectation operator conditioned on time zero information. The term, $\beta^t \upsilon_{t+j}$, is proportional to the state-contingent marginal value of a dollar to a household.[11] Also, β is a scalar between zero and unity. The timing of events for a firm is as follows. At the beginning of period t, the firm observes the technology shocks and sets its price, $P_t(i)$. Then, a shock to monetary policy is realized, as is the demand for the firm's product. The firm then chooses productive inputs to satisfy this demand. The problem of the i^{th} intermediate good firm is to choose prices, employment and capital services, subject to the timing and other constraints described above, to maximize (2.10).

2.1.3. Households

There is a continuum of households, indexed by $j \in (0, 1)$. The sequence of events in a period for a household is as follows. First, the technology shocks are realized. Second, the household makes its consumption and investment decisions. It also decides how many units of capital services to supply to rental markets. For reasons explained below, the household

[11] The constant of proportionality is the probability of the relevant state of the world.

purchases securities whose payoffs are contingent upon whether it can re-optimize its wage decision. Third, the household sets its wage rate. Fourth, the monetary policy shock is realized. Finally, the household allocates its beginning of period cash between deposits at the financial intermediary and cash to be used in consumption transactions.

Each household is a monopoly supplier of a differentiated labor service, and sets its wage subject to Calvo-style wage frictions. In general, households earn different wage rates and work different amounts. A straightforward extension of arguments in Erceg, Henderson and Levin (2000) and Woodford (1996) can be used to establish that, in the presence of the appropriate set of state contingent securities, households are homogeneous with respect to consumption and asset holdings. Our notation reflects this result.

The preferences of the j^{th} household are given by:

$$E_t^j \sum_{l=0}^{\infty} \beta^{l-t} \left[\log\left(C_{t+l} - bC_{t+l-1}\right) - \psi_L \frac{h_{j,t+l}^2}{2} \right], \tag{2.11}$$

where $\psi_L \geq 0$ and E_t^j is the time t expectation operator, conditional on household j's time t information set. The variable, C_t, denotes time t consumption and h_{jt} denotes time t hours worked. When $b > 0$, (2.11) allows for habit formation in consumption preferences.

The household's asset evolution equation is given by:

$$\begin{aligned} M_{t+1} &= R_t \left[M_t - Q_t + (x_t - 1)M_t^a\right] + A_{j,t} + Q_t + W_{j,t}h_{j,t} \\ &\quad + P_t r_t^k u_t \bar{K}_t + D_t - \left(1 + \eta\left(V_t\right)\right) P_t C_t - P_t \Upsilon_t^{-1} \left(I_t + a(u_t)\bar{K}_t\right). \end{aligned} \tag{2.12}$$

Here, M_t, Q_t and $W_{j,t}$ denote the household's beginning of period t stock of money, cash balances and time t nominal wage rate, respectively. In addition, $\bar{K}_t$, D_t and $A_{j,t}$ denote, the household's physical stock of capital, firm profits and the net cash inflow from participating in state-contingent securities at time t. The variable x_t represents the gross growth rate of the economy-wide per capita stock of money, M_t^a. The quantity $(x_t - 1)M_t^a$ is a lump-sum payment made to households by the monetary authority. The quantity, $M_t - Q_t + (x_t - 1)M_t^a$, is deposited by the household with a financial intermediary. The variable, R_t, denotes the gross interest rate.

The variable, V_t, denotes the time t velocity of the household's cash balances

$$V_t = \frac{P_t C_t}{Q_t}, \tag{2.13}$$

where $\eta(V_t)$ is increasing and convex. The presence of $\eta(V_t)$ in (2.12) captures the role of cash balances in facilitating transactions. Similar specifications have been used by a variety of authors including Sims (1994) and Schmitt-Grohe and Uribe (2004), among others. For the quantitative analysis of our model, we require the level and the first two derivatives of the transactions function, $\eta(V)$, evaluated in steady state. We denote these by η, η', and η'', respectively. We find it convenient to parameterize these objects as follows. In steady state, the model implies

$$\frac{\pi\mu_{z^*}}{\beta} = R,$$

where a variable without a time subscript denotes its non-stochastic steady state value. In addition, the first order condition for Q_t is:

$$R_t = 1 + \eta'\left(\frac{P_tC_t}{Q_t}\right)\left(\frac{P_tC_t}{Q_t}\right)^2.$$

Let ϵ_t denote the interest semi-elasticity of money demand:

$$\epsilon_t = -\frac{100 \times d\log(\frac{Q_t}{P_t})}{400 \times dR_t}.$$

Denote the curvature of η by σ_η:

$$\sigma_\eta = \frac{\eta'' V}{\eta'}.$$

Then, the first order condition for Q_t implies that the interest semi-elasticity of money demand in steady state is:

$$\epsilon = \frac{1}{4}\frac{1}{R-1}\frac{1}{2+\sigma_\eta}.$$

We parameterize $\eta(\bullet)$ indirectly using values for ϵ, V and η.

The remaining terms in (2.12) pertain to the household's capital related income. The services of capital, K_t, are related to stock of physical capital, $\bar{K}_t$, by

$$K_t = u_t\bar{K}_t,$$

where u_t denotes the utilization rate of capital. In (2.12), $P_tr_t^ku_t\bar{K}_t$ represents the household's earnings from supplying capital services. The function $a(u_t)\bar{K}_t$ denotes the cost, in investment goods, of setting the utilization rate to u_t. We assume $a(u_t)$ is increasing and convex. These assumptions capture the idea that the more intensely the stock of capital is utilized, the higher are maintenance costs in terms of investment goods. We assume that $u_t = 1$ in steady state and $a(1) = 0$. To implement our log-linear solution method, we must specify a value for the curvature of a in steady state, $\sigma_a = a''(1)/a'(1) \geq 0$. Although the steady state of the model does not depend on the value of σ_a, the dynamics do. Given our solution procedure, we do not need to specify any other features of the function a.

The household's stock of physical capital evolves according to:

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + F(I_t, I_{t-1}), \tag{2.14}$$

where δ denotes the physical rate of depreciation and I_t denotes time t investment goods. The function F summarizes the technology that transforms current and past investment into installed capital for use in the following period. As in CEE, we assume that investment adjustment costs are given by:

$$F(I_t, I_{t-1}) = (1 - S\left(\frac{I_t}{I_{t-1}}\right))I_t.$$

The function S is assumed to be increasing, convex and satisfies: $S = S' = 0$, and $S'' > 0$, in steady state. Although the steady state of the model does not depend on the value of S'', the dynamics do. Given our solution procedure, we do not need to specify any other features of the function S.

Note that in the budget constraint, the price of investment goods relative to consumption goods is assumed to be Υ_t^{-1}. As discussed above, we also assume that Υ_t^{-1} is an exogenous stochastic process. One way to rationalize these assumptions is that agents transform final goods into investment goods using a linear technology with slope Υ_t.This rationalization also underlies why we refer to Υ_t as capital embodied technological progress.

2.1.4. The Wage Decision

As in Erceg, Henderson and Levin (2000), we assume that the j^{th} household is a monopoly supplier of a differentiated labor service, h_{jt}. It sells this service to a representative, competitive firm that transforms it into an aggregate labor input, L_t, using the technology:

$$H_t = \left[\int_0^1 h_{jt}^{\frac{1}{\lambda_w}} dj\right]^{\lambda_w}, \ 1 \leq \lambda_w < \infty.$$

The demand curve for h_{jt} is given by:

$$h_{jt} = \left(\frac{W_t}{W_{jt}}\right)^{\frac{\lambda_w}{\lambda_w - 1}} H_t. \tag{2.15}$$

Here, W_t is the aggregate wage rate, i.e., the nominal price of H_t. It is straightforward to show that W_t is related to W_{jt} via the relationship:

$$W_t = \left[\int_0^1 (W_{jt})^{\frac{1}{1-\lambda_w}} dj\right]^{1-\lambda_w}. \tag{2.16}$$

The household takes H_t and W_t as given.

Households set their nominal wage according to a variant of the mechanism by which intermediate good firms set prices. In each period, a household faces a constant probability, $1-\xi_w$, of being able to re-optimize its nominal wage. The ability to re-optimize is independent across households and time. If a household cannot re-optimize its wage at time t, it sets W_{jt} according to:

$$W_{j,t} = \pi_{t-1}\mu_{z^*}W_{j,t-1}. \tag{2.17}$$

The presence of μ_{z^*} in (2.17) implies that there are no distortions from wage dispersion along the steady state growth path.

2.1.5. Monetary and Fiscal Policy

We adopt the following specification of monetary policy:

$$\hat{x}_t = \hat{x}_{zt} + \hat{x}_{\Upsilon t} + \hat{x}_{Mt}.$$

Here x_t represents the gross growth rate of money, M_t/M_{t-1}.We assume that

$$\begin{aligned} \hat{x}_{M,t} &= \rho_M \hat{x}_{M,t-1} + \varepsilon_{M,t} \\ \hat{x}_{z,t} &= \rho_{xz}\hat{x}_{z,t-1} + c_z\varepsilon_{z,t} + c_z^p\varepsilon_{z,t-1} \\ \hat{x}_{\Upsilon,t} &= \rho_{x\Upsilon}\hat{x}_{\Upsilon,t-1} + c_\Upsilon\varepsilon_{\Upsilon,t} + c_\Upsilon^p\varepsilon_{\Upsilon,t-1} \end{aligned} \tag{2.18}$$

Here, $\varepsilon_{M,t}$ represents a shock to monetary policy. We denote the standard deviation of $\varepsilon_{M,t}$ by σ_M. The dynamic response of $\hat{x}_{M,t}$ to $\varepsilon_{M,t}$ is characterized by a first order autoregression, so that ρ_M^j is the response of $E_t\hat{x}_{t+j}$ to a one-unit time t monetary policy shock. The term $\hat{x}_{z,t}$ captures the response of monetary policy to an innovation in neutral technology, $\varepsilon_{z,t}$. We assume that $\hat{x}_{z,t}$ is characterized by an ARMA(1,1) process. The term, $\hat{x}_{\Upsilon,t}$, captures the response of monetary policy to an innovation in capital embodied technology, $\varepsilon_{\Upsilon,t}$. We assume that $\hat{x}_{\Upsilon,t}$ is also characterized by an ARMA (1,1) process.

Finally, we assume that government adjusts lump sum taxes to ensure that its intertemporal budget constraint holds.

2.1.6. Loan Market Clearing, Final Goods Clearing and Equilibrium

Financial intermediaries receive $M_t - Q_t + (x_t - 1)\, M_t$ from the household, where our notation reflects the equilibrium condition, $M_t^a = M_t$. Financial intermediaries lend all of their money to intermediate good firms, which use the funds to pay labor wages. Loan market clearing requires

$$W_tH_t = x_tM_t - Q_t. \tag{2.19}$$

The aggregate resource constraint is

$$(1 + \eta(V_t))C_t + \Upsilon_t^{-1}\left[I_t + a(u_t)\bar{K}_t\right] \leq Y_t. \tag{2.20}$$

We adopt a standard sequence-of-markets equilibrium concept. In an appendix available upon request, we discuss our computational strategy for approximating that equilibrium.

This strategy involves taking a linear approximation about the non-stochastic steady state of the economy and using the solution method discussed in Christiano (2002).

2.2. The Firm - Specific Capital Model

In this subsection, we describe the version of the model in which capital is firm-specific. We assume that firms own their own capital. The capital that the firm begins the period with cannot be adjusted during the period. The firm can change its stock of capital by varying its rate of investment. In all other respects the problem of the intermediate good firm is the same as before. In particular, they face the same demand curve, (2.2), production technology, (2.4)-(2.8), and Calvo pricing frictions including the updating rule given by (2.9).

The technology for accumulating physical capital by intermediate good firm i is given by

$$F(I_t(i), I_{t-1}(i)) = (1 - S\left(\frac{I_t(i)}{I_{t-1}(i)}\right))I_t(i),$$

and

$$\bar{K}_{t+1}(i) = (1-\delta)\bar{K}_t(i) + F(I_t(i), I_{t-1}(i)).$$

The present discounted value of the i^{th} intermediate good's cash flow is given by:

$$E_t \sum_{j=0}^{\infty} \beta^j \upsilon_{t+j} \left\{ P_{t+j}(i) y_{t+j}(i) - P_{t+j} R_{t+j} w_{t+j}(i) h_t(i) - P_{t+j} \Upsilon_{t+j}^{-1} \left[I_{t+j}(i) + a\left(u_{t+j}(i)\right) \bar{K}(i)_{t+j} \right] \right\}. \tag{2.21}$$

The time t cash flow is sales, less labor costs (inclusive of interest charges) minus the costs associated with capital utilization and capital accumulation.

The sequence of events as it pertains to the i^{th} firm is as follows. At the beginning of period t, the firm has a stock of physical capital, $\bar{K}_t(i)$, which it takes as given. After observing the technology shocks, the firm sets its price, $P_t(i)$, subject to the Calvo frictions described previously. The firm also makes its investment and capital utilization decisions, $I_t(i)$ and $u_t(i)$, respectively. The time t monetary policy shock then occurs and the demand for the firm's product is realized. The firm then purchases labor to satisfy the demand for its output. Subject to these timing and other constraints, the problem of the firm is to choose prices, employment, the level of investment and utilization to maximize discounted cash flow.

2.3. Implications for Inflation

It is easy to verify that the equations which characterize equilibrium for the two variants of our model are identical except for the equation which characterizes the aggregate inflation dynamics. In both variants, this equation is of the form:

$$\Delta\hat{\pi}_t = E\left[\beta\Delta\hat{\pi}_{t+1} + \gamma\hat{s}_t|\Omega_t\right], \tag{2.22}$$

where

$$\gamma = \frac{\left(1-\xi_p\right)\left(1-\beta\xi_p\right)}{\xi_p}\zeta,$$

and Δ is the first difference operator. Here, Ω_t includes the current realization of the technology shocks, but not the current realization of the innovation to monetary policy. A hat over a variable, say x_t, denotes

$$\hat{x}_t = \frac{x_t - x}{x},$$

where absence of the subscript, t, indicates the nonstochastic steady state value. Also, s_t is the economy-wide average marginal cost of production, in units of the final good.

When we estimate the model, we find it convenient to parameterize the model in terms of γ, rather than ξ_p. With this change in parameterization, the list of parameters for the two models remains identical. Moreover, for a given set values for these parameters, the two models are observationally equivalent with respect to aggregate prices and quantities. In an appendix available upon request, we establish the following:

Proposition 1 (i) In the homogeneous capital model, $\zeta = 1$; (ii) In the firm-specific capital model, χ is a particular non-linear function of the parameters of the model.

3. Econometric Methodology

To estimate and evaluate the empirical plausibility of our model, we employ a variant of the limited information strategy used in CEE. The basic idea is to impose a subset of the assumptions made in our equilibrium model to estimate the impulse response functions of ten key macroeconomic variables to neutral technology shocks, capital embodied technology shocks and monetary policy shocks. We then describe an estimation strategy for our equilibrium model which chooses values for key parameters that minimize the difference between the estimated impulse response functions and the analogous objects in our model.

We now describe our identification assumptions, and the strategy for estimating the dynamic response of the economy to the three shocks in our model. Our identifying assumptions are satisfied by the models described in section 2.

3.1. Identification of Impulse Responses

Our identifying assumptions for monetary policy shocks correspond to the recursive approach used in Christiano, Eichenbaum and Evans (1999). The identifying assumptions are (i) there is exactly one shock, - the monetary policy shock - that affects the interest rate contemporaneously, but which does not affect aggregate prices and quantities contemporaneously, and (ii) the monetary policy shock is uncorrelated with all other shocks. We refer the reader to

Christiano, Eichenbaum and Evans (1999) for an extensive discussion of these identifying assumptions.

To identify the shock to technology, we adopt the strategy used by Fisher (2003) who modifies the methods used Gali (1999), Gali, Lopez-Salido, and Valles (2002) and Francis and Ramey (2002) in order to separately identify neutral and capital embodied shocks to technology. In particular, we assume that innovations to technology (both neutral and capital embodied) are the only shocks that affect the level of labor productivity in the long run. In addition, we assume that capital embodied technology shocks are the only shocks that affect the price of investment goods relative to consumption goods in the long run. These assumptions are satisfied in our model.

To make precise our identifying assumption and estimation strategy, it is useful to consider the following *reduced form* vector autoregression:

$$\begin{aligned} Y_t &= \alpha + B(L)Y_{t-1} + u_t, \\ Eu_t u_t' &= V, \end{aligned} \tag{3.1}$$

where $B(L)$ is a q^{th}-ordered polynomial in the lag operator, L. The 'fundamental' economic shocks, e_t, are related to u_t as follows:

$$u_t = Ce_t,\ Ee_t e_t' = I, \tag{3.2}$$

where C is a square matrix. To calculate the dynamic response of Y_t to a disturbance in the i^{th} fundamental shock, e_{it}, we require $B(L)$ and the i^{th} column of C, C_i.

In our empirical analysis, we work with a ten-dimensional vector, Y_t:

$$\underbrace{Y_t}_{10\times 1} = \begin{pmatrix} \Delta\ln(\text{relative price of investment}_t) \\ \Delta\ln(GDP_t/\text{Hours}_t) \\ \Delta\ln(GDP\text{ deflator}_t) \\ \text{capacity utilization}_t \\ \ln(\text{Hours}_t) \\ \ln(GDP_t/\text{Hours}_t) - \ln(W_t/P_t) \\ \ln(C_t/GDP_t) \\ \ln(I_t/GDP_t) \\ \text{Federal Funds Rate}_t \\ \ln(GDP\text{ deflator}_t) + \ln(GDP_t) - \ln(MZM_t) \end{pmatrix} = \begin{pmatrix} \underbrace{\Delta p_{It}}_{1\times 1} \\ \underbrace{\Delta a_t}_{1\times 1} \\ \underbrace{Y_{1t}}_{6\times 1} \\ \underbrace{R_t}_{1\times 1} \\ \underbrace{Y_{2t}}_{1\times 1} \end{pmatrix} \tag{3.3}$$

According to our economic model, the variables in Y_t are stationary stochastic processes. We partition e_t conformably with the partitioning of Y_t :

$$e_t = \left(\underbrace{e_{\Upsilon,t}}_{1\times 1}\ \underbrace{e_{z,t}}_{1\times 1}\ \underbrace{e_{1t}'}_{1\times 6}\ \underbrace{e_{Mt}}_{1\times 1}\ \underbrace{e_{2t}}_{1\times 1} \right)'.$$

Here, e_{zt} is proportional to the innovation to a neutral technology shock $(\varepsilon_{\mu_z,t})$, $e_{\Upsilon,t}$ is proportional to the innovation in capital-embodied technology $(\varepsilon_{\mu_\Upsilon,t})$, and e_{Mt} is proportional to the monetary policy shock $(\varepsilon_{M,t})$.

An alternative representation of our system is given by the *structural form*:

$$A_0 Y_t = A(L)Y_{t-1} + e_t. \tag{3.4}$$

The parameters of the reduced form are related to those of the structural form by:

$$C = A_0^{-1},\ B(L) = A_0^{-1}A(L). \tag{3.5}$$

We obtain impulse responses by first estimating the parameters of the structural form, mapping these into the reduced form, and then simulating (**??**).

3.1.1. Monetary Policy Shocks

We assume that policy makers manipulate the monetary instruments under their control in order to ensure that the following interest rate targeting rule is satisfied:

$$R_t = f(\Omega_t) + \varepsilon_{Rt}, \tag{3.6}$$

where ε_{Rt} is the monetary policy shock. We interpret (3.6) as a reduced form Taylor rule. To ensure identification of the monetary policy shock, we assume f is linear, Ω_t contains Y_{t-1}, ..., Y_{t-q} and the only date t variables in Ω_t are $\{\Delta a_t, \Delta p_{It}, Y_{1t}\}$. Finally, we assume that ε_{Rt} is orthogonal with Ω_t. It is easy to verify that these identifying assumptions correspond to the following restrictions on A_0:

$$A_0 = \begin{bmatrix} \underset{1\times1}{A_0^{1,1}} & \underset{1\times1}{A_0^{1,2}} & \underset{6\times6}{A_0^{1,3}} & \underset{1\times1}{0} & \underset{1\times1}{0} \\ \underset{1\times1}{A_0^{2,1}} & \underset{1\times1}{A_0^{2,2}} & \underset{1\times6}{A_0^{2,3}} & \underset{1\times1}{0} & \underset{1\times1}{0} \\ \underset{6\times1}{A_0^{3,1}} & \underset{6\times1}{A_0^{3,2}} & \underset{6\times6}{A_0^{3,2}} & \underset{6\times1}{0} & \underset{6\times1}{0} \\ \underset{1\times1}{A_0^{4,1}} & \underset{1\times1}{A_0^{4,2}} & \underset{1\times6}{A_0^{4,3}} & \underset{1\times1}{A_0^{4,4}} & \underset{1\times1}{0} \\ \underset{1\times1}{A_0^{5,1}} & \underset{1\times1}{A_0^{5,2}} & \underset{1\times6}{A_0^{5,3}} & \underset{1\times1}{A_0^{5,4}} & \underset{1\times1}{A_0^{5,5}} \end{bmatrix}. \tag{3.7}$$

The second to last row of A_0 corresponds to the monetary policy rule, (3.6). The zero in this row reflects our assumption that Ω_t does not include the last variable in Y_t. The right two columns of zeros in the first 8 rows of A_0 reflect our assumption that a monetary policy shock has no contemporaneous impact on Δa_t, Δp_{It} or Y_{1t}. The zeros in column 4 reflect our assumption that the first 8 variables do not depend on the interest rate, and therefore the monetary policy shock. The zeros in column 5 rule out the possibility that the policy shock affects the first 8 variables indirectly by way of its impact on the last variable in Y_t.

3.1.2. Technology Shocks

As stated above, we assume that the only shocks which have a non-zero impact on the level of productivity at infinity are innovations to neutral and capital-embodied technology. The only shock that has an effect on the price of investment at infinity is a shock to capital-embodied technology.

3.2. Estimation of Impulse Responses

To discuss our estimation strategy, it is useful to write out the equations of the structural system explicitly, taking into account the restrictions implied by our assumptions about long-run effects of shocks and our assumptions about the effects of a monetary policy shock.

Apart from a constant, the first equation in (3.4) can be written as follows:

$$\Delta p_{It} = a_{11}(L)\Delta p_{It-1} + a_{12}(L)\Delta^2 a_t + a_{13}(L)\Delta Y_{1t} + a_{14}(L)\Delta R_{t-1} + a_{15}(L)\Delta Y_{2,t-1} + \frac{e_{\Upsilon,t}}{A_0^{1,1}}, \quad (3.8)$$

where $\Delta \equiv (1 - L)$. Here the polynomial lag operators correspond to the relevant entries of the second row of $A_0 - A(L)L$, scaled by $A_0^{1,1}$. Imposing the restriction that only capital embodied technology shocks have a non-zero impact on the relative price of investment at infinity is equivalent to imposing a unit root in each of the lag polynomials associated with Δa_t, Y_{1t}, R_{t-1} and $Y_{2,t-1}$. Also note that we exclude the contemporaneous values of R_t and Y_{2t} from the right side of (3.8). This reflects our assumption that monetary policy shocks do not have a contemporaneous impact on the price of investment (see the discussion about A_0 above). We cannot use ordinary least squares to obtain a consistent estimate of the coefficients in (3.8) because $\Delta^2 a_t$ and ΔY_{1t} are in general correlated with $e_{\Upsilon,t}$. We apply two stage least squares to estimate the parameters using as instruments a constant, Δa_{t-i}, Δp_{It-i}, Y_{1t-i}, R_{t-i}, and Y_{2t-i}, $i = 1, 2, 3, 4$. The coefficients in the first row of the structural form can then be obtained by scaling the instrumental variables estimates up by $A_0^{1,1}$, where $A_0^{1,1}$ is estimated as the (positive) square root of the variance of the fitted disturbance in the instrumental variables relation.

The second equation in (3.4) can be written as:

$$\Delta a_t = a_{22}(L)\Delta a_{t-1} + a_{21}(L)\Delta p_{It} + a_{23}(L)\Delta Y_{1t} + a_{24}(L)\Delta R_{t-1} + a_{25}(L)\Delta Y_{2,t-1} + \frac{e_{zt}}{A_0^{2,2}}, \quad (3.9)$$

where the polynomial lag operators correspond to the relevant entries of the second row of $A_0 - A(L)L$, scaled by $A_0^{2,2}$. The presence of a unit root in the polynomial lag operators multiplying Y_{1t}, R_{t-1} and $Y_{2,t-1}$ reflects our assumption that non-technology shocks have no impact on a_t at infinity[12]. Our assumptions do not imply a similar unit root restriction on

[12] For further discussion , see Shapiro and Watson (1988), and the more recent papers by Christiano, Eichenbaum and Vigfusson (2003, 2003a, 2003b) and Fisher (2003).

the polynomial lag operator multiplying Δp_{It}. This is because, by assumption, the moving average relating non capital-embodied technology shocks to Δp_{It} already has a unit root. The fact that the contemporaneous values of R_t and Y_{2t} are excluded from (3.9) reflects our assumption that monetary policy shocks do not have a contemporaneous impact on labor productivity (see the discussion about A_0 above).

We cannot use ordinary least squares to obtain a consistent estimate of the coefficients in (3.9), because e_{zt} is, in general, correlated with Δp_{It} and ΔY_{1t}. Instead, we apply two-stage least squares using as instruments a constant, $\hat{e}_{\Upsilon,t}$, Δa_{t-i}, Δp_{It-i}, Y_{1t-i}, R_{t-i}, and $Y_{2,t-i}$, for $i = 1, 2, 3, 4$. Here, $\hat{e}_{\Upsilon,t}$ is the fitted disturbance from (3.8). By including this disturbance as an instrument, we are imposing our assumption that neutral and capital-embodied technology shocks are orthogonal. The coefficients in the second row of the structural form can be obtained by scaling the instrumental variables estimates up by $A_0^{2,2}$. Here, $A_0^{2,2}$ is estimated as the (positive) square root of the variance of the fitted disturbances in the instrumental variables relation.

The next set of 6 equations in (3.4) can be written as follows:

$$A_0^{3,1}\Delta a_t + A_0^{32}\Delta p_{It} + A_0^{3,3}Y_{1t} = b(L)Y_{t-1} + e_{1t} \tag{3.10}$$

The ninth equation in (3.4) is just the policy rule:

$$R_t + \frac{A_0^{4,1}}{A_0^{4,4}}\Delta p_{It} + \frac{A_0^{4,2}}{A_0^{4,4}}\Delta a_t + \frac{A_0^{4,3}}{A_0^{4,4}}Y_{1t} = c(L)Y_{t-1} + \frac{e_{Mt}}{A_0^{4,4}}. \tag{3.11}$$

Consistent estimates of the parameters in (3.11) can be obtained by ordinary least squares with R_t as the dependent variable. This is because, by assumption, e_{Mt} is not correlated with Δa_t, Δp_{It} and Y_{1t}. The fitted e_{Mt}'s are orthogonal to e_{zt}'s and $e_{\Upsilon t}$'s. This is e_{Mt}'s are orthogonal to the variables that span the space in which the innovations to technology lie. The parameters of the 9^{th} row of the structural form are obtained by scaling the estimates up by $A_0^{3,3}$, where $A_0^{3,3}$ is estimated as the positive square root of the variance of the fitted residuals. Finally, according to the last equation:

$$Y_{2t} + \frac{A_0^{5,1}}{A_0^{5,5}}\Delta a_t + \frac{A_0^{5,2}}{A_0^{5,5}}\Delta p_{It} + \frac{A_0^{5,3}}{A_0^{5,5}}Y_{1t} + \frac{A_0^{5,4}}{A_0^{5,5}}R_t = d(L)Y_{t-1} + \frac{e_{2t}}{A_0^{5,5}}.$$

The coefficients in this relation can be estimated by ordinary least squares. This is because e_{2t} is not correlated with the other contemporaneous variables in this relation. This reflects that Y_{2t} does not enter any of the other equations. The parameter, $A_0^{5,5}$, can be estimated as the square root of the estimated variance of the disturbances in this relation. The parameters in the last row of the structural form are then estimated suitably scaling up by $A_0^{5,5}$

The previous argument establishes that rows 1, 2, 9 and 10 of A_0 are identified. The block of 6 rows in the middle is not identified. To see this, let w denote an arbitrary

6×6 orthonormal matrix, $ww' = I_6$. Suppose $\bar{A}_0$ and $\bar{A}(L)$ is some set of structural form parameters that satisfies all our restrictions. Let the orthonormal matrix, W, be defined as follows:

$$W = \begin{bmatrix} \underset{2\times 2}{I} & \underset{2\times 6}{0} & \underset{2\times 2}{0} \\ \underset{6\times 2}{0} & \underset{6\times 6}{w} & \underset{6\times 2}{0} \\ \underset{2\times 2}{0} & \underset{2\times 6}{0} & \underset{2\times 2}{I} \end{bmatrix}. \tag{3.12}$$

It is easy to verify that the reduced form corresponding to the parameters, $W\bar{A}_0$, $W\bar{A}(L)$ also satisfies our restrictions, and leads to the same reduced form:

$$Y_t = \left(W\bar{A}_0\right)^{-1} W\bar{A}(L)Y_{t-1} + \left(W\bar{A}_0\right)^{-1} We_t.$$

To see this, note:

$$\begin{aligned} \left(W\bar{A}_0\right)^{-1} W\bar{A}(L) &= \bar{A}_0^{-1}W'W\bar{A}(L) = \bar{A}_0^{-1}\bar{A}(L) \\ E\left(W\bar{A}_0\right)^{-1} Wu_tu_t'W'\left[\left(W\bar{A}_0\right)^{-1}\right]' &= E\bar{A}_0^{-1}W'We_te_t'W'\left[\bar{A}_0^{-1}W'\right]' \\ &= \bar{A}_0^{-1}\left(\bar{A}_0^{-1}\right)'. \end{aligned}$$

Recall that impulse response functions can be computed using the matrices in $B(L)$ and the columns of A_0^{-1}. It is easy to see that the impulse responses to e_{Mt}, e_{zt} and $e_{\Upsilon t}$ are invariant to w. This is because:

$$\left(W\bar{A}_0\right)^{-1} = \bar{A}_0^{-1}W'.$$

It can be verified that columns 1, 2, 9 and 10 of $\bar{A}_0^{-1}W'$ coincide with those of $\bar{A}_0^{-1}$.

We conclude that there is a family of observational equivalent parameterizations of the structural form, which is consistent with our identifying assumptions on the monetary policy shock and the technology shocks. We arbitrarily select an element in this family as follows. Let Q and R be orthonormal and lower triangular (with positive diagonal terms) matrices, respectively, in the QR decomposition of A_0^{33}. That is, $A_0^{33} = QR$. This decomposition is unique and guaranteed to exist given that A_0^{33} is non-singular, a property implied by our assumption that A_0 is invertible. The reasoning up to now indicates that we may, without loss of generality, select A_0 so that A_0^{33} is lower triangular with positive diagonal elements. This restriction does not restrict the reduced form in any way, nor does it restrict the set of possible impulse response functions associated with e_{Mt}, e_{zt}, $e_{\Upsilon,t}$ or e_{2t}.

Thus, in (3.10) A_0^{33} is lower triangular. We seek consistent estimates of the parameters of (3.10), with this restriction imposed. Ordinary least squares will not work as an estimation procedure here because of simultaneity. To see this, consider the first equation in (3.10). Suppose the left hand variable is the first element in Y_{1t}. The only current period explanatory variables are Δa_t and Δp_{It}. But, note from the first and second equations in the structural form that Δa_t and Δp_{It} respond to Y_{1t} and, hence, to the innovations in Y_{1t}. That is, Δa_t and Δp_{It} is correlated with the first element in e_{1t}. We can instrument for Δa_t using e_{zt}, the (scaled) residual from the first structural equation, and for Δp_{It} using $e_{\Upsilon,t}$, the (scaled) residual from the second structural equation.

Now consider the second equation in (3.10). Think of the left hand variable as being the second variable in Y_{1t}. The current period explanatory variables in that equation are $\Delta a_{t,}$ Δp_{It} and the first variable in Y_{1t}. All of these variables are correlated with the second element in e_{1t}. To see this, note that a disturbance in the second element of e_{1t} ends up in Δa_t and Δp_{It} via the first and second equations in the structural form, because Y_{1t} appears in those equations. This explains why Δa_t and Δp_{It} are correlated with the second element of e_{1t}. But, the first element in Y_{1t} is also correlated with this variable because Δa_t and Δp_{It} are 'explanatory' variables in the equation determining the first element in Y_{1t}, i.e., the first equation in (3.10). So, we need an instrument for Δa_t, Δp_{It} and the first element of Y_{1t}. For this, use e_{zt}, $e_{\Upsilon,t}$ and the residual from the first equation in (3.10). Thus, moving down the equations in (3.10), we use as instruments e_{zt}, $e_{\Upsilon,t}$ and the disturbances in the previous equations in (3.10).

With A_0 and $A(L)$ in hand, we are now in a position to compute the reduced form, using (3.5). The dynamic responses of Y_t to technology and monetary policy shocks may be computed by simulating (**??**) with $i = 1, 2, 9$, respectively.

3.3. The Estimation Criterion

Here, we describe the estimation strategy implemented in CEE (see also Rotemberg and Woodford (1997)). Let ζ denote the model parameters that we estimate. Let $\Psi(\zeta)$ denote the mapping from ζ to the model impulse response functions, and let $\hat{\Psi}$ denote the corresponding estimates obtained by the strategy described above. We include the first 20 elements of each response function, excluding those that are zero by assumption. Our estimator of ζ is the solution to:

$$\hat{\zeta} = \arg\min_{\zeta} (\hat{\Psi} - \Psi(\zeta))' V^{-1} (\hat{\Psi} - \Psi(\zeta)). \tag{3.13}$$

Here, V is a diagonal matrix with the sample variances of the $\hat{\Psi}$'s along the diagonal. These variances are the ones that were used to construct the confidence intervals described in Figures 2-4. With this choice of V, $\hat{\zeta}$ is the value of ζ which ensures that $\Psi(\zeta)$ lies as much as possible inside the confidence intervals in Figures 2-4. We compute standard errors for $\hat{\zeta}$ using the delta-function method.[13]

[13] Let the criterion in (3.13) be denoted $L(\zeta, \hat{\Psi}) \equiv (\hat{\Psi} - \Psi(\zeta))' V^{-1} (\hat{\Psi} - \Psi(\zeta))$, so that $L_1(\hat{\zeta}, \hat{\Psi}) = 0$. Denote the mapping in (3.13) by $\hat{\zeta} = f(\hat{\Psi})$. To obtain the sampling variance of the estimator, $\hat{\zeta}$, as a function of the sampling variance of $\hat{\Psi}$, the delta function method approximates $f(\hat{\Psi})$ by its linear expansion about the true value of Ψ, Ψ^0. That is, $f(\hat{\Psi}) \approx f(\Psi^0) + f'(\Psi^0)(\hat{\Psi} - \Psi^0)$. Here, $f(\Psi^0) = \zeta^0$, where ζ^0 is the true value

4. Estimation Results Based on Identified Vector Autoregressions

In this section we describe the dynamic response of the economy to monetary policy shocks, and the two technology shocks. In addition, we discuss the quantitative contribution of these shocks to the cyclical fluctuations in aggregate economic activity. In the first subsection we describe the data used in the analysis. In the second and third subsections we discuss the impulse response functions and the importance of the shocks to aggregate fluctuations.

4.1. Data

The data used in the analysis were taken from the DRI Basic Economics Database.[14] We need to take a stand on the mapping between real consumption, investment and output in our model and the analog objects in the data. There are two issues concerning the measurement of Our equilibrium model assumes that productivity growth, the interest rate, inflation, the log consumption to output ratio, the log investment to output ratio, log capacity utilization, log per capita hours worked, the log of the productivity to real wage ratio, and the log of GDP velocity are all stationary. These variables are graphed in Figure 1. Thin lines indicate the raw data. For the most part, the data appear consistent with our stationarity assumption. Our data are quarterly and cover the period is 1959QI - 2001QIV. [15].

All of our data correspond to standard measures, except for our choice of monetary

of ζ, by the consistency of our estimator. Then, $\sqrt{T}(\hat{\zeta}_T - \zeta^0)$ is asymptotically Normally distributed with mean zero and variance $f'(\Psi^0)Wf'(\Psi^0)^T$, where the superscript T indicates the transposition operator, and W is the asymptotic variance-covariance matrix of $\sqrt{T}(\hat{\Psi} - \Psi)$. We use the implicit function theorem to approximate $f'(\Psi^0)$ by $-L_{11}(\zeta^0, \Psi^0)^{-1}L_{12}(\zeta^0, \Psi^0)$. This discussion has assumed that V is not random. In practice, we use the sample-based object discussed in the text. In addition, W is replaced by its sample estimate, as are ζ^0 and Ψ^0 in the expression for f'. As noted in the text, V is a diagonal matrix composed of the diagonal elements of W.

[14] The data were taken from http://economics.dri-wefa.com/webstract/index.htm. Nominal gross output is measured by GDP, real gross output is measured by $GDPQ$ (real, chain-weighted output). Nominal investment is GCD (household consumption of durables) plus GPI (gross private domestic investment). Nominal consumption is measured by GCN (nondurables) plus GCS (services) plus GGE (government expenditures). Our MZM measure of money was obtained by splicing the Federal Reserve Bank of St. Louis' measure, 'M2 minus' (this is M2, less small time deposits and has mnemonic M2MSL) with their MZM measure (mnemonic MZMSL). Both data series are monthly, and were converted to quarterly using end-of-quarter observations. The splice was accomplished by replacing the M2 minus data with MZM beginning in 1974. No scaling was done to implement the splice since the two series are essentially the same in 1974. These variables were converted into per capita terms by $P16$, a measure of the US population over age 16. A measure of the aggregate price index was obtained from the ratio of nominal to real output, $GDP/GDPQ$. Capacity utilitzation is measured by IPXMCA the manufacturing industry's capacity index (there is a measure for total industry, IPX, but it only starts in 1967). The interest rate is measured by the federal funds rate, $FYFF$. Hours worked is measured by LBMNU (Nonfarm business hours). Hours were converted to per capita terms using our population measure. Nominal wages are measured by LBCPU, (nominal hourly non-farm business compensation). This was converted to real terms by dividing by the aggregate price index.

[15] The estimation period drops the first 4 quarters, to accommodate the 4 lags.

aggregate. We digress to discuss the properties of our measure of money - the St. Louis Fed's MZM - and why we chose to work with this monetary aggregate. Our statistical procedure requires that the velocity of money - whether measured in terms of consumption or output - is stationary. Figure 2 displays velocity for M1, M2 and MZM. It is evident that the only monetary aggregate for which velocity is plausibly stationary is MZM. In terms of our equilibrium model, the relevant concept of money is the one tied to transactions balances. MZM is designed to measure this concept. Interestingly, MZM velocity moves closely with the Federal Funds rate (see Figure 1). This is consistent with the implications of our equilibrium model. We return to this point below, when we analyze the quantitative properties of the estimated version of that model.

4.2. Estimated Impulse Response Functions

In this subsection we discuss the results of implementing the procedure discussed above to estimate the dynamic effects of monetary policy and technology shocks. Figure 3 displays the response of our variables to a monetary policy shock. In each case, there is a solid line in the center of a gray area. The gray area represents a 95 percent confidence interval, and the solid line represents the point estimates.[16] (The dotted line will be discussed later.) Note that the variables displayed in Figure 3 are transformations of the variables in Y_t, which are displayed in Figure 1. Except for inflation and the interest rate, all variables are expressed in percent terms. Thus, the peak response of output is a little over 0.2 percent. The Federal Funds rate is in units of basis points, at an annual rate. For example, the policy shock produces a contemporaneous 60 basis point drop in the federal funds rate. Inflation is expressed at a quarterly rate.

There are six features worth emphasizing here. First, the effect of a policy shock on the money growth rate and the interest rate is completed within roughly one year. The other variables respond over a longer period of time. Second, there is a significant liquidity effect, i.e. the interest rate and money growth move in opposite directions after a policy shock.[17] Third, after an initial fall, inflation rises before reaching its peak response in roughly two years. Fourth, output, consumption, investment, hours worked and capacity utilization all display hump-shaped responses, which peak after roughly one year. Fifth, velocity falls for roughly the amount of time that the interest rate is below its pre-shock level. After this, it rises in a persistent, hump-shaped manner. Finally, the real wage and the price of investment do not respond significantly to a monetary policy shock.

[16] The confidence intervals are symmetric about our point estimates. They are obtained by adding and subtracting 1.96 times our estimate of the standard errors of the coefficients in the impulse response functions. These were computed by bootstrap simulation of the estimated model.

[17] In interpreting our measure of money, MZM, as a policy variable, we implicitly assume that the monetary authority can achieve any degree of control over MZM that it wishes by suitably manipulating bank reserves.

Next we discuss the estimated response of the economy to a positive neutral technology shock, displayed in Figure 3. All responses are measured in the same units as in Figures 1 and 2. By construction, the impact of the technology shock on output, labor productivity, consumption, investment and the real wage can be permanent. Because the roots of our estimated VAR are stable, the impact of a neutral technology shock on the variables whose levels appear in Y_t must be temporary. These variables include capacity utilization, hours worked and inflation.

Figure 3 indicates that, a one-standard deviation positive neutral technology shock leads to a persistent rise in output, with a peak rise of roughly 0.6 percent over the period displayed. In addition, hours worked responds strongly in the first year after the shock, with a peak effect of roughly 0.5 percent. Both investment and consumption display a strong response. Capacity utilization also rises but the response is not statistically significant. Both velocity and the price of investment show marginally significant drops in response to the shock. Finally notice that a neutral technology shock leads a sharp, persistent fall in the rate of inflation. Overall, these effects are broadly consistent with what a student of real business cycle models might expect. This contrasts with recent papers which make the same identifying assumptions about a neutral technology as we do. However, these papers argue that hours worked fall in the wake of a positive, neutral technology shock. Christiano, Eichenbaum and Vigfusson (2003a, 2003b) argue that the reason for this difference is that authors like Gali (1999) and Francis and Ramey (2001) work with the first difference rather than the levels of hours worked. Christiano, Eichenbaum and Vigfusson (2003) argue on statistical grounds that first differencing hours worked amounts to a specification error, and that the quantitative findings in those papers can be explained by this error.[18]

Figure 4 indicates that a one standard deviation positive capital embodied technology shock leads to marginally significant rises in output, hours worked and the federal funds rate. Most strikingly, investment responds strongly to the shock, with an initial peak response of over 2 percent. In addition, the shock leads to an initial fall in the price of investment of roughly 0.3 percent, followed by an ongoing significant decline.

4.3. The Contribution of Monetary Policy and Technology Shocks to Aggregate Fluctuations

Figures 6-9 provide a visual representation of the cyclical importance of the three shocks that we estimated under our identifying assumptions. The thick line in Figure 6 displays a simulation of the 'detrended' historical data. The detrending is achieved like this. First, we simulated the estimated reduced form representation (3.1) using the fitted disturbances, $\hat{u}_t$,

[18] Christiano, Eichenbaum and Vigfusson (2003) also dismiss findings that hours worked fall after a positive technology shock, based on analyses in which hours worked has been adjusted by a quadratic trend.

but setting the constant term, α, and the initial conditions of Y_t to zero. In effect, this gives us a version of the data, Y_t, in which any dynamic effects from unusual initial conditions (relative to the VAR's stochastic steady state) have been removed, and in which the constant term has been removed. Second, the resulting 'detrended' historical observations on Y_t are then transformed appropriately to produce the variables reported in Figure 6. The high degree of persistence observed in output in Figure 6 reflects that our procedure for computing it makes it the realization of a random walk with no drift.

The procedure used to compute the thick line in Figure 6 was then repeated, with one change, to produce the thin line. Rather than using the historical reduced form shocks, $\hat{u}_t$, the simulations underlying the thin line use $\hat{A}_0^{-1}\hat{e}_t$, allowing only the 1^{st}, 2^{nd} and 9^{th} elements of $\hat{e}_t$ to be non-zero. Here, $\hat{e}_t$ is our estimate of the fundamental shocks, obtained from $\hat{e}_t = \hat{A}_0\hat{u}_t$. The overall impression is that our three shocks account for a substantial fraction of the variation in all the variables except for the real wage. It is particularly worth noting that the identified shocks account well for the drop in output in the 1970, 1973, and 1980/1981 recessions (NBER recession dates are indicated by the gray areas). Figures 7-9 are the analogs to Figure 6, when only one shock is operative (neutral technology shock, capital embodied shock and monetary policy shock, respectively). Three things are worth noting. First, from Figure 7 we see that, at least up to 1990, neutral technology shocks play an important role in the medium and long-run frequencies for variables like output, inflation, average hours, real wages and investment. Interestingly, these shocks also play some role at the longer frequencies for the price of investment up to around 1982 but not thereafter. For consumption, these shocks play a large role at medium and long frequencies for the whole sample period. Second, from Figure 8 we see that capital embodied technology shocks play an important role in explaining medium and long-run movements in the price of investment, particularly after 1982. From Figure 9 we see that monetary At the same time, monetary policy shocks do not play an important role in the price of investment (see Figure 9) This is consistent with the equilibrium model described in section xx. Third, monetary policy shocks play a significant role in the cyclical component of output.

Tables 1 and 2 report quantitative measures of the contribution of our shocks to the variance in different variables. Consider Table 1. The column labelled HP 1600 displays the percent variance of the HP-filtered data accounted for by our three shocks simultaneously. The column labelled BP (8,32) displays the corresponding object for frequencies between 8 and 32 quarters, as isolated by the band pass filter.[19] As is well known, the HP 1600 is similar to a high pass filter, which lets through all variation with period 32 quarters and higher. So, the difference between the HP and BP filters is that the latter allows high frequency

[19]For the HP filter we set the parameter λ to 1600. For the band pass filter, we used the random walk version recommended by Christiano and Fitzgerald (2002).

variation to pass through. According to Table 1, our shocks account for roughly 75 percent of the business cycle variation in output and hours. In addition, when the high frequency component of the data are also included, as in the HP filter, the percent of the variance accounted for by our identified shocks falls slightly. This may reflect that measurement error (not included among our three shocks) is relatively more important in the higher frequencies. Our three shocks also account for a large proportion of the cyclical variation in other variables like inflation, the federal funds rate, capacity utilization, consumption, investment velocity and the price of investment, and to a lesser extent MZM growth. However the shocks account for virtually none of the cyclical variation in real wages.

Table 2 reports the percent of variance due to monetary policy shocks alone. The results in the table indicates that monetary policy shocks play a very important role in the cyclical variation of all the variables, except for the real wage and the price of investment. For example, these shocks account for roughly 31 percent (HP filter) and 42 percent (BP filter) of the cyclical variation in output. Based on the BP filter, we conclude that monetary policy shocks also account for roughly 50 percent of the cyclical variation in the consumption and velocity and roughly 38 percent of the cyclical variation in MZM growth, and capacity utilization. These shocks account for roughly 30 percent of the cyclical variation in investment.

It is worth emphasizing that the results in Table 2 do not contradict existing results in the literature about the importance of different shocks in aggregate time series data. The latter are usually quantified using forecast error variance decompositions, which stress a greater range of frequencies of the data, than either the HP or BP filter results (see, for example, CEE.) According to Table 2, ,monetary policy shocks account for less than 6 percent of the forecast error variance at horizon 30 quarters. Interestingly, monetary policy shocks do account for a large percent of the forecast error variance of MZM growth and the federal funds rate, at various horizons.

Viewed overall, the results of this subsection can be summarized as follows. First, the three shocks that we estimated under our identifying assumption account for a large fraction of the time series variation in all the variables under consideration except for real wages. Second, monetary policy shocks play a very important role in cyclical fluctuations. Together the two technology shocks account for about as much of the cyclical variation in economic activity as monetary policy shocks. Interestingly, monetary policy shocks play a much smaller role at medium and long run frequencies for aggregate quantities than at cyclical frequencies, while technology shocks (especially the neutral shocks) play a much larger role. This is what a student of standard growth models would anticipate.

5. Estimation Results for the Equilibrium Model Based on Impulse Response Functions

In this section we discuss the estimated parameter values. In addition, we assess the ability of the estimated model to account for the impulse response functions discussed in section ??.

5.1. Benchmark Parameter Estimates

We partition the parameters of the model into three groups. The first group of parameters, ζ_1, pertain to the 'non-stochastic' part of the model, and are given by:

$$\zeta_1 = [\beta, \alpha, \delta, \phi, \psi_L, \lambda_w, \mu_\Upsilon, \mu_z, x, V, \eta] .$$

These were set a priori based on the considerations discussed below. The second set of parameters, ζ_2, which also pertain to the 'non-stochastic part' of the model, are:

$$\zeta_2 = [\lambda_f, \xi_w, \gamma, \sigma_a, b, \varkappa, \epsilon] .$$

The third set of parameters, ζ_3, also were estimated and pertain to the stochastic part of the model:

$$\zeta_3 = \left[\rho_M, \sigma_M, \rho_{\mu_z}, \sigma_{\mu_z}, \rho_{xz}, c_z, c_z^p, \rho_{\mu_\Upsilon}, \sigma_{\mu\Upsilon}, \rho_{x\Upsilon}, c_\Upsilon, c_\Upsilon^p\right] .$$

The first two parameters in ζ_3 characterize the monetary policy shock (see (2.18).) The next five characterize the evolution of the disembodied technical shock, as well as the monetary policy response to that shock. The last five parameters are the analogous objects that correspond to the embodied shock to technology. Thus, the total number of parameters to be estimated based on the impulse responses are 19.

We now discuss the values that we assume for ζ_1. We set $\beta = 1.03^{-0.25}$, which implies a steady state annualized real interest rate of 3 percent. We set $\alpha = 0.36$, which corresponds to a steady state share of capital income equal to roughly 36 percent.[20] We set $\delta = 0.025$, which implies an annual rate of depreciation on capital equal to 10 percent. This value of δ is roughly equal to the estimate reported in Christiano and Eichenbaum (1992). The parameter, ϕ, is set to guarantee that profits are zero in steady state. For a discussion of this way of choosing ϕ, see Basu and Fernald (1994), Hall (1988), and Rotemberg and Woodford (1995). As in CEE, we set the parameter, λ_w, to 1.05.

The parameter μ_Υ was set to 1.0042. This corresponds to the negative of the average growth rate of the price of investment relative to the GDP deflator which fell at an annual

[20] In our model, the steady state share of labor income in total output is $1 - \alpha$. A key assumption in our model that underlies this result is that profits are zero in steady state.

average rate of 1.68 percent over our sample period. The steady state growth of real per capita GDP, μ_y, is given by

$$\mu_y = \left(\mu_\Upsilon\right)^{\frac{\alpha}{1-\alpha}} \mu_z.$$

The average growth rate of per capita GDP in our sample implies $\mu_y = 1.0045$. Solving the previous equation for μ_z yields $\mu_z = 1.00013$. This is the value of μ_z used in our analysis. The average growth rate of money, μ_x, was set equal to 1.017.This value corresponds to the average quarterly growth rate of our measure of money over our sample period.

The parameters V and η were set to 1.43 and 0.036, respectively. The value of V corresponds to the average value of P_tC_t/M_{t+1} in our sample. We chose η so that, in conjunction with the other parameter values of our model, the steady state value of $\eta C/Y$ is 0.025. This corresponds to the percent of value-added in the finance, insurance and real estate industry (see Christiano, Motto and Rostagno (2004)).

The row labeled 'benchmark' in Table 5 summarizes our point estimates of the parameters in the vector ζ_1. Standard errors are reported in parentheses. The lower bound of unity is binding on λ_f, and so we simply set λ_f to 1.01 in the estimation of the model. Our point estimate of ξ_w implies that wage contracts are re-optimized, on average, once every 3.6 quarters. To interpret our point estimate of γ, recall that in the homogeneous capital model, $\gamma = (1-\xi_p)(1-\beta\xi_p)/\xi_p$. So our point estimate of γ implies a value of ξ_p equal to 0.83, i.e. firms re-optimize prices roughly every 6 quarters. This is considerably longer than the findings in Golosov and Lucas (2003) and Klenow and Kryvtsov (2003), which suggest that firms change prices roughly once every 1.7 quarters. If instead we adopt the assumption that capital is firm specific, then we find that firms reoptimize on average once every 1.6 quarters.[21] Evidently, the impact of firm specific capital is quantitatively large. This is a central result of this paper. Below, we analyze the reasons why the firm-specific and homogeneous capital versions of the model give rise to such different implications for ξ_p.

To interpret the estimated value of σ_a, it is useful to consider the homogeneous capital model. Linearizing the household's first order condition for capital utilization about steady state yields

$$E_{t-1}\left[\frac{1}{\sigma_a}\hat{r}_t^k - \hat{u}_t\right] = 0.$$

According to this expression, $1/\sigma_a$ is the elasticity of capital utilization with respect to the rental rate of capital. Our estimated value of this elasticity is substantially smaller than the one reported in CEE. Our esimate of σ_a implies that it is relatively costly for firms to vary the utilization of capital.

Our point estimate of the habit parameter b is 0.65. This value is close to the point estimate of 0.66, reported in CEE and the value of 0.7 reported in Boldrin, Christiano and

[21] This number was obtained using the algorithm discussed in Appendix A.

Fisher (2001). The latter authors argue that the ability of standard general equilibrium models to account for the equity premium and other asset market statistics is considerably enhanced by the presence of habit formation in preferences.

We now discuss our point estimate of $\varkappa$. Suppose we denote by $P_{k',t}$ the shadow price of one unit of $\bar{k}_{t+1}$,in terms of output. The variable $P_{k',t}$ is what the price of installed capital would be in the homogeneous capital model if there were a market for $\bar{k}_{t+1}$ at the beginning of period t. Proceeding as in CEE, it is straightforward to show that the household's first order condition for investment implies:

$$\hat{\imath}_t = \hat{\imath}_{t-1} + \frac{1}{\varkappa} \sum_{j=0}^{\infty} \beta^j E_{t-1} \hat{P}_{k',t+j}.$$

According to this expression, $1/\varkappa$ is the elasticity of investment with respect to a one percent temporary increase in the current price of installed capital. Our point estimate implies that this elasticity is equal to 0.45. The more persistent is the change in the price of capital, the larger is the percentage change in investment. This is because adjustment costs induce agents to be forward looking.

According to our point estimate of ϵ is roughly unity. That is, a one percentage point increase in the annualized rate of interest induces a one percent decline in real transactions balances. This elasticity is smaller than what Lucas (1988) and others obtain when they estimate static money demand equations. We suspect that the difference in result reflects that our estimation criterion places relatively more weight on the high frequency movements in money and interest rates.

We now consider the estimated values for the parameters that pertain to the stochastic part of the model. These are reported in Table 4. With these values, the law of motion for the neutral and capital embodied technology shocks can be written as:

$$\hat{\mu}_{z,t} = 0.92\hat{\mu}_{z,t-1} + \varepsilon_{\mu_z,t},\ \sigma_{\mu_z} = 0.06$$

$$\hat{\mu}_{\Upsilon,t} = 0.21\hat{\mu}_{\Upsilon,t-1} + \varepsilon_{\mu_\Upsilon,t},\ \sigma_{\mu_\Upsilon} = 0.31$$

According to our estimates, shocks to neutral technology exhibit a high degree of serial correlation, while shocks to capital embodied technology shocks do not. It is interesting to compare our results for $\hat{\mu}_{z,t}$ with the ones reported in Prescott (1986), who estimates the properties of the technology shock process using the Solow residual. He finds the shock is roughly a random walk and its growth rate has a standard deviation of roughly 1 percent.[22]

[22] Prescott (1986) actually reports a standard deviation of 0.763 percent. However, he adopts a different normalization for the technology shock than we do, by placing it in front of the production function. Instead, our technology shock multiplies labor directly in the production and is taken to a power of labor's share. The value of labor's share that Prescott uses is 0.70. When we translate Prescott's estimate into the one relevant for our normalization, we obtain $0.763/.7 \approx 1$.

By contrast, our estimates imply that the unconditional standard deviation of the growth rate of neutral technology is roughly 0.15 percent. So, estimates imply that technology shocks are less volatile but more persistent than according to Prescott's estimates. In principle, these differences reflect two factors. First, from the perspective of our model, Prescott's estimate of technology confounds technology with variable capital utilization. Second, our analyses are based on different data sets. Prescott's calculations are based on Solow residual accounting, which use data on capital, labor and output. We do not use data on the capital stock, but we do use data on all the variables in our 10 variable VAR.

To understand the implications of our point estimates of the parameters of monetary policy, it is useful to consider the dotted lines in the bottom right-hand corners of Figures 3, 4 and 5. There, we display the response of total money growth, i.e., M_{t+1}/M_t, to a monetary policy shock, a neutral technology, and a capital-embodied technology shock, respectively. A number of features of the estimated policy rules are worth noting. First, the response of total money growth to a policy shock is short-lived. Second, total money growth responds positively and persistently, to a neutral technology shock. So, consistent with results in Gali, et. al. (2003), we find that monetary policy is accommodative with respect to this shock. Third, total money growth also increases in a very persistent manner in response to a capital embodied technology shock. Below, we discuss how the economy would have responded if the Fed had not been accommodative with respect to both technology shocks.

5.2. Properties of the Estimated Model

The dotted lines Figures 3 -5 display the impulse response functions of the estimated model to monetary policy, neutral technology shocks and capital embodied shocks. Recall that the solid lines and the associated confidence intervals (the gray areas) pertain to the impulse response functions from the identified VARs.

5.2.1. Response to a Monetary Policy Shock

We begin by discussing the model's performance with respect to a monetary policy shock. A number of results are worth emphasizing here. First, consistent with results in CEE, the model does well at accounting for the dynamic response of the US economy to a monetary policy shock. Most of the model responses lie within the two-standard deviation confidence interval computed from the data. It is particularly noteworthy that the model succeeds in accounting for the inertial response of inflation. Indeed, there is no noticeable rise in inflation until roughly a year after the policy shock. This is true even though firms in the firm-specific capital version of the model change prices quite often, i.e., on average once every 1.6 quarters.

Second, the model generates a very persistent response in output. The peak effect occurs roughly one year after the shock. The output response is positive for roughly two years. Third, the model is able to account for the dynamic response of the interest rate to a monetary policy shock. Consistent with the data, an expansionary monetary policy shock induces a sharp decline in the interest rate which then returns to its pre-shock level within a year. Also notice that according to the model, the growth rate of transactions balances (i.e., MZM) rises for a brief period of time after the policy shock, but then quickly reverts to its pre-shock level. It is evident that the effects of a policy shock on aggregate economic activity persist beyond the effects on the policy variable itself. This property reflects the strong internal propagation mechanisms in the model.

Fourth, as in the data, the real wage remains essentially unaffected by the policy shock. Fifth, consumption, investment, and hours worked exhibit persistent, hump-shaped rises that are consistent with our VAR-based estimates. Sixth, consistent with the data, velocity falls after the expansionary policy shock. Basically this reflects that money demand rises with the initial fall in the interest rate. As the interest rate begins to move towards its pre-shock level and consumption rises, velocity also rises. However, these forces are not sufficiently strong to render the model consistent with the strong rise in velocity estimated from the identified VAR roughly 5 quarters after the policy shock. Seventh, note that by construction, the relative price of investment is not affected by a policy shock in the model. At least for the first two years after the policy shock, this is roughly consistent with the response of the relative price of investment to a policy shock in the identified VAR. Finally, capacity utilization in the model rises by only a very small amount, and understates the rise that is estimated to occur in the data. This is an important point which we return to below.

5.2.2. Response to a Neutral Technology Shock

We now discuss the model's performance with respect to a neutral technology shock, displayed in Figure 4. A number of key features are worth noting. First, the model does well at accounting for the dynamic response of the U.S. economy to a neutral technology shock. Specifically, the model accounts for the rise in aggregate output, hours worked, investment, consumption and the real wage. Second, the model somewhat understates the decline in velocity as well as the price of investment that occur after an expansionary neutral technology shock. Third, the model does not capture the fall in inflation that occurs after the shock. This reflects the strong response of money growth required to allow the estimated model to capture the general rise in economic activity after the shock. To see this, consider the solid lines Figure 10, which display the response of the model economy to a positive, neutral, technology shock under the assumption that money growth remains unchanged from its steady state level (the dotted lines reproduce the response of the estimated model economy, taken from Figure 4.) The key things to note are that absent monetary accommodation the output response is weak, hours worked fall and inflation declines. Evidently, the estimation criterion prefers to match the output and employment response at the cost of doing less well on the inflation response.

We conclude that in terms of the quantity variables, the model economy responds qualitatively to a neutral technology shock in the same way that a real business analyst would anticipate. Ironically, according to our model the strong, short run expansionary effects of a neutral technology shock are due to the accommodative nature of monetary policy.

5.2.3. Response to a Capital Embodied Technology Shock

We now discuss the model's performance with respect to a capital embodied technology shock, displayed in Figure 5. The model does very well in accounting for the response of the US economy to this shock, except that it understates the rise in capacity utilization.

Figure 5 indicates that monetary policy is accommodative with respect to a capital embodied technology shock. To see the importance of monetary policy in the transmission of capital embodied technology shocks, Figure 11 displays the response of output, inflation, the interest rate and hours worked under the assumption that money growth remains unchanged from its steady state level. Notice that under this assumption, output and hours worked rise by much less, while inflation falls. We conclude that, as with neutral technology shocks, monetary policy plays an important role in the transmission of capital embodied technology shocks.

6. The Key Features of the Model

In this section we discuss the key features of the data that drive our parameter estimates. We then discuss why these parameter estimates imply that the firm-specific and homogeneous capital models have such different implications for the frequency with which firms reoptimize prices.

Recall that our point estimate of γ is 0.035, which implies that a temporary 1 percent change in marginal cost results in only a 0.031 percent change in the aggregate price level. This low value of γ lies at the heart of the tension between the micro and macro implications of the homogeneous capital model. The low value of γ that we estimate is consistent with estimates reported in the literature.[23] As it turns out, it is straightforward to see why any reasonable estimate of γ must be low. In Figure 12a we plot $\Delta\hat{\pi}_t - \beta\Delta\hat{\pi}_{t+1}$ versus our measure of the log of marginal cost, $\hat{s}_t$.[24] Notice that the distribution of $\Delta\hat{\pi}_t - \beta\Delta\hat{\pi}_{t+1}$ is

[23] See Eichenbaum and Fisher (2004) and the references therein.

[24] We set $\beta = 1.03^{-.25}$. Also, we measure marginal productivity by labor's share in GDP. In our model this

at best weakly related to the magnitude of $\hat{s}_t$.[25] The relatively flat curve in the figure has a slope equal to our point estimate of γ (0.035). Significantly, this curve passes through the central tendency of the data. Now consider $\gamma = 0.9$. This is the value of γ implied by the version of the homogeneous capital model in which firms change prices once every 1.7 quarters. The steeper curve in Figure 12a is drawn for this value of γ. Clearly, raising γ leads to a drastic deterioration in fit.

Technically speaking, (2.22) implies that the magnitude of the residuals from the lines in Figure 12a are not per se a good measure of model fit. But, there is reason to focus on the size of residuals when the data are replaced by their projection onto date t information. This is because in this case, (2.22) implies that least squares consistently recovers the true value of γ. Figure 12b is the analog to Figure 12a, with variables replaced by their projection onto $\digamma_t \equiv \{\Delta\pi_{t-s} - \beta\Delta\pi_{t+1-s}, \hat{s}_{t-s}; s = 1, 2\}$. Notice that Figures 12a and 12b are very similar. Our conclusions are unchanged: the data on inflation and marginal cost suggest that γ is small.[26]

The low estimated value of γ provides a different perspective on the inflation inertia puzzle, particularly the weak response of inflation to monetary policy shocks. To see this, solve (2.22) forward to obtain

$$\Delta\hat{\pi}_t = \gamma \sum_{j=0}^{\infty} \beta^j E_t \hat{s}_{t+j}. \tag{6.1}$$

This relation makes clear why many authors have sought to account for inflation inertia by incorporating model features like variable capital utilization and sticky wages, which can reduce the response of expected marginal cost to shocks.[27] Relation (6.1) reveals another way to account for inflation inertia, namely, assigning a small value to γ. The evidence in Figure 12 indicates that a small value of γ must be part of any successful resolution of the inflation inertia puzzle.

A low value of γ is clearly a problem for the homogeneous capital model. This is because the model then implies that firms reoptimize prices very infrequently, e.g., at intervals of 6 quarters or more.[28] Subject to our caveats about the distinction between price changes and price reoptimization, this means that getting the macro data right (i.e., a low γ) implies that the model gets the micro data wrong. Now suppose that the model gets the micro data right, so that we assume that firms reoptimize prices on average once every 1.7 quarters.

is the correct measure if fixed costs are zero. This measure is approximately correct here, since our estimate of ϕ is close to zero.

[25] Eichenbaum and Fisher (2004) that their estimates of γ are robust to alternative measures of marginal cost.

[26] We obtain the same results whether we work with $\Delta\hat{\pi}_t$ or with $\hat{\pi}_t$.

[27] See, for example, Ball and Romer (1990), CEE, Dotsey and King (2001) and Smets and Wouters (2003).

[28] This is a straightforward implication of the homogeneous capital model discussed above, according to which $\gamma = (1 - \xi_p)(1 - \beta\xi_p)/\xi_p$.

Then the homogeneous capital model implies $\gamma = 0.9$. So, the model gets the macro data wrong.

To understand how the firm-specific capital model reconciles the micro and macro data, recall the intuition discussed in the introduction. In the firm-specific capital model, marginal cost is increasing in output. In the homogeneous capital model marginal cost is constant. Figure 13 displays the inititial marginal cost curves of the homogeneous and firm-specific capital models, denoted by $MC_{0,h}$ and $MC_{0,f}$. Notice that both these curves intersect the marginal revenue curve at point A.So, both firms produce the same amount, Q_0, and set the same price, P_0. Now consider the effect of an exogenous shock which pushes both marginal cost curves in a parallel way, by the same amount, to $MC_{1,h}$ and $MC_{1,f}$. In the homogeneous capital model, the marginal revenue and new marginal curve intersect at the point, B. The new price chosen is P_1. In the firm-specific capital model, the intersection of marginal cost and revenue occurs at B'. Note that the new price chosen is P_2. The key thing to note is that $P_1 > P_2$. The steeper is the slope of the marginal cost curve, the lower is P_2. Since the aggregate price level is just the average of individual firm prices, this intuition explains why increasing the slope of the marginal cost curve in our model reduces the value of γ.

The key parameter which governs the slope of our marginal cost curve is σ_a. The larger is this parameter, the flatter is the marginal cost curve. This explains our numerical finding that for a given value of γ, ξ_p is a decreasing function of σ_a. In fact, our point estimate of σ_a is large. This helps explain why the value of ξ_p implied by the firm-specific model is low.

What is it about the data that leads to a large point estimate for σ_a? We recomputed the impulse responses implied by our model, holding all but one of the model parameters at their estimated values. The exception, σ_a, was set to 0.01. There were three effects of this change. Two effects are that there is an increase the response of utilization to neutral and disembodied technology shocks. From Figures 4 and 5 it is not surprising that a stronger response of utilization would move that response above the confidence intervalThe key effect of this change on the model impulse responses is to change the sign of the response of investment to a neutral technology shock. In the benchmark model, investment rises in response to such a shock (see Figure 4). With the lower value of σ_a, investment falls. Our estimation criterion selects a high value for σ_a because investment rises in response to a positive, neutral technology shock in our estimated VAR.

So, why does investment fall when σ_a is small? A positive, serially correlated shock to the growth rate of technology creates a strong, positive income effect. In the table, we report that the $\rho_{\mu_z} = 0.8$, so that a one percent innovation in z_t creates the expectation that z_t will eventually rise by five times as much. Agents' desire to smooth consumption creates an incentive to raise consumption and reduce investment by a large amount in the period of the shock.[29] At the same time, the technology shock raises the rate of return on capital, and this acts to raise investment. When σ_a is large the rate of return effect dominates, so that investment rises in the wake of a neutral technology shock. When σ_a is small, capital utilization rises with the technology shock, and this works to reduce the rate of return on capital. Now the income effect dominates the rate of return effect, which is why investment falls.

The logic in the previous paragraph rests centrally on two results: (i) a rise in neutral technology raises utilization and (ii) increased utilization reduces the rate of return on capital. We established these properties of our estimated model by numerical simulation. To understand the economic forces underlying (i) and (ii), it is useful to establish them analytically in a sharply simplified version of our model. Consider a neoclassical growth model with variable capital utilization, but with fixed hours worked, no money, perfect competition, no price frictions, no adjustment costs in investment, and no habit persistence. In this model the equilibrium allocations solve the following planning problem. Maximize, by choice of capital utilization, investment and consumption, the following criterion:

$$\sum_{t=0}^{\infty} \beta^t u(C_t),$$

subject to the following constraint:

$$C_t + \bar{K}_{t+1} \leq f(\bar{K}_t, u_t, z_t) \equiv \left(u_t \bar{K}_t\right)^{\alpha} z_t^{1-\alpha} + (1 - \delta - a(u_t))\bar{K}_t.$$

As above, the capital utilization function, a, satisfies restrictions which ensure that u_t is unity in nonstochastic steady state. The planner's first order condition for u_t equates the marginal benefit of utilization, $\alpha u_t^{\alpha-1} \left(\bar{K}_t\right)^{\alpha} z_t^{1-\alpha}$, with the marginal cost, $a'(u_t)\bar{K}_t$. Note that the marginal benefit converges to infinity as $u_t \to 0$ and it converges to zero as $u_t \to \infty$. Because $a'' > 0$, the marginal cost is strictly increasing. This and the properties of marginal benefit imply that the two curves cross exactly once. >From this and the fact that an increase in z_t shifts up the benefits of utilization without affecting the costs, we infer that u_t is an increasing function of z_t. This establishes (i). Next, notice that in steady state we have $a' = MP_{\bar{K}}$. Here, $MP_{\bar{K},t}$ is the derivative of $f(\bar{K}_t, u_t, z_t)$ with respect to $\bar{K}_t$ and $MP_{\bar{K}}$ is $MP_{\bar{K},t}$ evaluated in steady state. The rate of return on capital in this economy is $f_{\bar{K},t} = MP_{\bar{K},t} + 1 - \delta - a(u_t)$. Note that $dMP_{\bar{K},t}/du_t = \alpha MP_{\bar{K},t}/u_t$, which is just $\alpha MP_{\bar{K}}$ in steady state. So, $df_{\bar{K},t}/du_t = \alpha MP_{\bar{K},t}/u_t - a'(u_t)$ and in steady state this expression is:

$$\begin{aligned} & \alpha MP_{\bar{K}} - a' \\ = \; & (\alpha - 1)MP_{\bar{K}} < 0. \end{aligned} \tag{6.2}$$

[29] For recent discussions of this idea in general equilibrium models, see Edge, Laubach and Williams (2004) and Linde (2004).

This establishes property (ii) in the neighborhood of steady state. Increased utilization gives rise to two effects. On the one hand it raises the marginal physical product of capital. On the other hand, it raises the utilization costs of capital. According to (6.2), the second effect dominates. This is why increased utilization reduces the rate of return on capital.

To verify our intution about why our benchmark estimate of σ_a is high, we reestimated the model including only the responses to a monetary policy shock in the criterion. Our results appear in Table 6. Note that our point estimate of σ_a falls from 2.01 to 0.007. The lower value of σ_a allows the model to better capture the estimated rise in capital utilization that occurs after a monetary policy shock, without paying a penalty for the counterfactual implication that investment falls after a neutral technology shock.[30]

A high elasticity of demand (i.e., λ_f is low), also works to reduce a firm's incentive to raise price. That is, a low λ_f reduces γ. The firm-specific capital model reconciles our low estimate of γ with a low ξ_p because the estimated value of λ_f is low and the estimated value of σ_a is high.

Recall that our estimation strategy focuses on γ, and not ξ_p. In particular, the estimated values λ_f and σ_a have nothing to do any assumed desirable values for ξ_p. So, why did the estimation results for λ_f and σ_a come out the way they did? Regarding σ_a, we found that a smaller value of σ_a has the implication that investment falls after a positive shock to neutral technology. Our VAR-based estimates suggest this is counterfactual.[31] In the case of λ_f, we found that our estimation criterion is very insensitive to λ_f, though it weakly prefers a very low value for this variable. We found that the low value of λ_f is crucial for allowing the model to reconcile a low value of γ with a low value of ξ_p. So, if we assume that firms reoptimize frequently, then the small value of γ virtually compels us to select a value of λ_f close to unity.

7. Choosing Between the Homogeneous and Firm-Specific Capital Models

Given our benchmark parameters in Table 5, the homogeneous and firm-specific capital versions of the model imply that firms reoptimize prices on average once every 6 and 1.6 quarters, respectively. The aggregate data do not allow us to differentiate between these two versions of our model. In this section, we use the microeconomic implications of the models to distinguish between them.

Bils and Klenow (2002), Lucas and Golosov (2003) and Klenow and Kryvtsov (2002)

[30] This reconciles our results with those reported in CEE, who report a low estimated value of σ_a based on an estimation criterion that includes only the responses to a monetary policy shock.

[31] Discuss intuition behind role of variable capital utilization in determine investment response to neutral technology shock.

argue, using microeconomic data that firms change prices on average more frequently than once every two quarters. The distinction between price changes and price reoptimization aside, this evidence favors the firm-specific capital version of the model. In this section we document an even more powerful reason for preferring that version of the model. In particular, we consider the cross-firm distribution of prices and output after a monetary policy shock. To this, we suppose that the economy is in a steady state up until period 0. In the steady state, each firm's price and quantity is the same. We suppose that an expansionary monetary policy shock occurs in period 1. Given the timing convention in our model, prices and output levels are the same across firms at the end of period 1. In period 2, a fraction, $1-\xi_p$, of firms reoptimize their price. The complementary fraction updates their price according to (2.9). In period 3 there are four types of firms: (i) a fraction, $\left(1-\xi_p\right)^2$, of firms that reoptimize in periods 2 and 3; (ii) a fraction, ξ_p^2, of firms that do not reoptimize in periods 2 or 3; (iii) a fraction, $\left(1-\xi_p\right)\xi_p$, which reoptimize in period 2 and not in period 3; and (iv) a fraction, $\xi_p\left(1-\xi_p\right)$, of firms that do not reoptimize in period 2, but do reoptimize in period 3. In period s there are 2^{s-1} different types of firms. For $s=4$, 8 and 16, we calculated the distribution of output and relative prices for the different types of firms. Figure 13 summarizes the findings for the homogeneous capital version of the model. The three rows in Figure 13 pertain to the situation in periods 4, 8 and 16, respectively. Consider the first row. Note the integers 1, 2, 3, and 4 on the horizontal axes. The first of these pertains to firms that did not reoptimize their price in periods 2, 3 and 4. The integers, j, $j=2,3$ and 4, pertain to firms who last reoptimized in period j. The graph on the left shows the share of output (black bars) and the fraction of firms (grey bars) produced by the different types of firms. (In the homogeneous capital model, the price and output levels of all firms within each of these four groups are the same.) The graph on the right shows the relative price of the firms in each of these groups. The other two rows are the analogs of the first row, except that they pertain to the situation in periods 8 and 16, respectively.

Several features of Figure 13 are worth noting. First, in the first few years of the shock a small fraction of the firms are producing a disproportionate share of the output. Indeed, our linearized solution implies they produce more than 100 percent of output and firms who can reoptimize price, set their price so high that their output is negative. We do not take seriously the negative level of output per se. We conjecture that in the actual solution firms that produce negative amounts in our solution actually are shutting down. The implication that a large fraction of firms cease to produce in the wake of a one-standard deviation shock to the interest rate is clearly implausible. What is driving these implausible implications is the high elasticity of demand for the firm's output when λ_f is small. So, this implication could be avoided by imposing a larger value of λ_f. So, it is possible to rescue the homogeneous capital model from this implication by imposing a higher value of λ_f. But, in our view this is not a satisfactory way to rescue the homogeneous capital model. This is because, when we impose $\lambda_f = 1.20$ and reestimate the model, we still find that ξ_p is implausibly high.

Figure 14 is the analog of Figure 13, except that it pertains to the firm-specific capital model. A number of features are worth noting. First, consistent with the low value of ξ_p in this version of the model, in each of periods 4, 8 and 16, more than half the firms reoptimize their price. Second, the dramatic degree of inequality of production associated with the homogeneous capital model is not present here. Still, there is some inequality. For example, in period 4, firms that have not reoptimized their price since period 1 produce a share of output that is roughly three times their proportion in the population. In later periods, the extent of the inequality in production is substantially mitigated.[32]

We conclude that the microeconomic implications of the estimated homogeneous capital model are clearly implausible. The corresponding implications of the firm-specific capital model are not clearly implausible. On this basis, we prefer the firm-specific capital version of the model. But, without data on the response of the actual cross-firm distribution of output and prices to a monetary policy shock, we cannot claim more.

8. Accuracy of Impulse Response Functions

This section will discuss Figures 16-18, which document the accuracy of our VAR methods for estimating impulse response functions from data generated using our estimated equilibrium model. The simulation method explicitly takes into account our VAR-based estimate of the degree of variation in the data coming from shocks other than the three that we identify. In each figure, the solid, black line indicates the 'true' impulse response functions in the Monte Carlo simulations. These are the responses in our estimated equilibrium model. In each case, the dotted lines are the median, in repeated samples of 160 artificial observations each, of the impulse response functions estimated using our 4-lag, 10 variable VAR. The grey areas are 95 percent intervals indicating the range of variation across artificial samples in the impulse reponse functions. The dashed lines indicate the probability limit of the VAR estimator of the impulse response functions. We estimated this by simulating a single sample of length 20,000 observations. The key thing to note is that there is very little small sample bias in our estimator. Two exceptions occur in the response of output and consumption to a neutral technology shock (see Figure 18). This discrepancy is reduced when the number of lags in the VAR is extended to 6. This motivated us to redo our analysis for a six lag VAR. We found that the results are essentially unchanged.

[32] One measure of the degree of inequality in production is provided by the Gini coefficient. In periods 4, 8 and 16, these are 0.24, 0.40 and 0.68 for firm-specific capital version of the model.

9. Conclusion

We constructed a dynamic general equilibrium model of cyclical fluctuations. Given assumptions satisfied by our model, we identified dynamic response of key US economic aggregates to 3 shocks: Monetary Policy Shocks, Neutral Technology Shocks and Capital Embodied Technology Shocks. These shocks account for roughly 75% of cyclical variation in output. The estimated general equilibrium model does a good job of accounting for response functions. Sticky prices play a very limited role in the model's performance. This conclusion depends on assuming capital is firm specific.

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Table1
Combined Impact of Shocks To Cyclical Variance

Variable	HP 1600	BP 8-32
Output	64.40	74.74
MZM Growth	27.70	40.93
Inflation	53.98	63.70
Fed Funds	52.30	60.70
Capacity Util.	50.94	56.46
Avg. Hours	58.11	75.78
Real Wage	4.87	2.98
Consumption	74.22	95.26
Investment	55.87	63.26
Velocity	39.56	55.77
Price of Inv.	59.10	56.16

Table 2: Contribution of Embodied Technology Shocks to Cyclical Variance

Variable	Forecast Variance at Indicated Horizion					Business Cycle Frequencies	
	1	4	8	12	30	HP 1600	BP 8-32
Output	21.90	23.53	18.72	13.85	11.21	20.99	26.50
MZM Growth	0.95	1.24	2.30	4.01	5.66	4.42	10.17
Inflation	3.20	3.37	8.69	8.14	4.79	9.23	15.01
Fed Funds	1.16	13.88	17.26	15.20	10.17	14.58	22.21
Capacity Util.	6.15	11.71	10.72	16.79	13.91	21.08	25.39
Avg. Hours	19.31	25.08	20.73	16.14	11.02	20.85	30.05
Real Wage	1.20	0.57	1.00	1.98	9.32	1.96	1.59
Consumption	3.66	17.11	13.05	9.54	7.33	15.19	25.08
Investment	28.36	33.44	33.50	28.62	38.75	20.94	23.05
Velocity	2.42	4.80	7.38	5.01	3.70	12.06	22.54
Price of Inv.	81.27	72.39	64.74	60.35	53.08	41.82	37.73

Table 3: Contribution of Neutral Technology Shocks to Cyclical Variance

Variable	Forecast Variance at Indicated Horizion					Business Cycle Frequencies	
	1	4	8	12	30	HP 1600	BP 8-32
Output	29.63	28.04	36.21	39.19	52.57	10.46	9.93
MZM Growth	0.26	0.73	0.93	1.56	2.66	1.15	0.55
Inflation	51.16	47.06	42.52	39.86	44.35	28.35	19.48
Fed Funds	2.79	0.93	0.65	0.66	23.32	2.45	1.33
Capacity Util.	2.25	2.09	2.51	2.23	5.67	4.15	2.61
Avg. Hours	6.48	17.88	29.63	32.48	31.19	8.21	8.86
Real Wage	1.42	3.46	7.62	11.01	19.90	1.87	0.97
Consumption	37.29	39.23	54.97	64.07	76.69	18.48	16.87
Investment	7.33	10.09	12.35	10.67	13.43	5.80	5.78
Velocity	0.99	0.23	1.32	5.07	40.14	5.60	0.96
Price of Inv.	2.98	0.97	1.01	1.76	12.51	4.50	1.45

Table 4: Contribution of Monetary Policy Shocks to Cyclical Variance

Variable	Forecast Variance at Indicated Horizion					Business Cycle Frequencies	
	1	4	8	12	30	HP 1600	BP 8-32
Output	0.00	5.26	6.67	5.05	5.98	31.23	42.02
MZM Growth	17.99	18.02	19.72	18.88	18.75	24.08	38.02
Inflation	0.00	1.42	5.45	8.57	6.27	16.11	29.16
Fed Funds	68.97	24.64	16.46	18.01	12.70	40.59	49.36
Capacity Util.	0.00	5.86	10.58	8.30	14.22	31.55	38.32
Avg. Hours	0.00	5.19	11.43	11.25	9.10	29.69	44.33
Real Wage	0.00	0.04	0.27	1.05	1.11	2.38	2.88
Consumption	0.00	5.12	3.69	2.20	2.88	29.79	50.44
Investment	0.00	4.68	5.97	4.94	5.63	25.53	31.97
Velocity	14.22	4.06	7.86	13.01	7.81	37.77	61.21
Price of Inv.	0.00	0.37	0.41	1.46	2.44	8.57	7.56

TABLE 5: ESTIMATED PARAMETER VALUES ζ_1							
Model	λ_f	ξ_w	γ	σ_a	b	$\varkappa$	ϵ
Benchmark	1.01	.72 (.03)	.035 (.009)	2.01 (.62)	.65 (.05)	2.22 (.45)	1.06 (.13)
Benchmark Money Shocks Only	1.02 (.06)	.66 (.02)	.12 (.02)	.007 (.03)	.68 (.05)	2.72 (.48)	1.04 (.10)
High Markup	1.20	.66 (.03)	.04 (.01)	1.51 (.44)	.64 (.05)	1.93 (.38)	1.03 (.12)
Low Cost of Varying Capital Utilization	1.01	.64 (.02)	.10 (.03)	0.1	.68 (.05)	2.05 (.42)	1.03 (.12)

TABLE 6: ESTIMATED PARAMETER VALUES ζ_2											
ρ_M	σ_M	ρ_{μ_z}	σ_{μ_z}	ρ_{xz}	c_z	c_z^p	ρ_{μ_Υ}	σ_{μ_Υ}	$\rho_{x\Upsilon}$	c_Υ	c_Υ^p
Benchmark Model											
.24 (.09)	.26 (.02)	.92 (.02)	.06 (.006)	.37 (.20)	3.36 (.62)	1.19 (1.22)	.21 (.12)	.31 (.04)	.67 (.08)	.38 (.13)	.26 (.14)
Benchmark Model. Money Shocks Only											
.26 (.08)	.25 (.02)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
High Markup											
.23 (.09)	.25 (.03)	.91 (.02)	.06 (.006)	.36 (.19)	3.32 (.62)	1.21 (1.20)	.19 (.12)	.32 (.04)	.69 (.08)	.42 (.13)	.18 (.14)
Low Cost of Varying Capital Utilization											
.25 (.08)	.25 (.02)	.87 (.02)	.06 (.006)	.37 (.18)	3.55 (.64)	1.44 (1.25)	−.11 (.179)	.30 (.04)	.68 (.08)	.28 (.14)	.36 (.14)

Figure 1: data used in the analysis

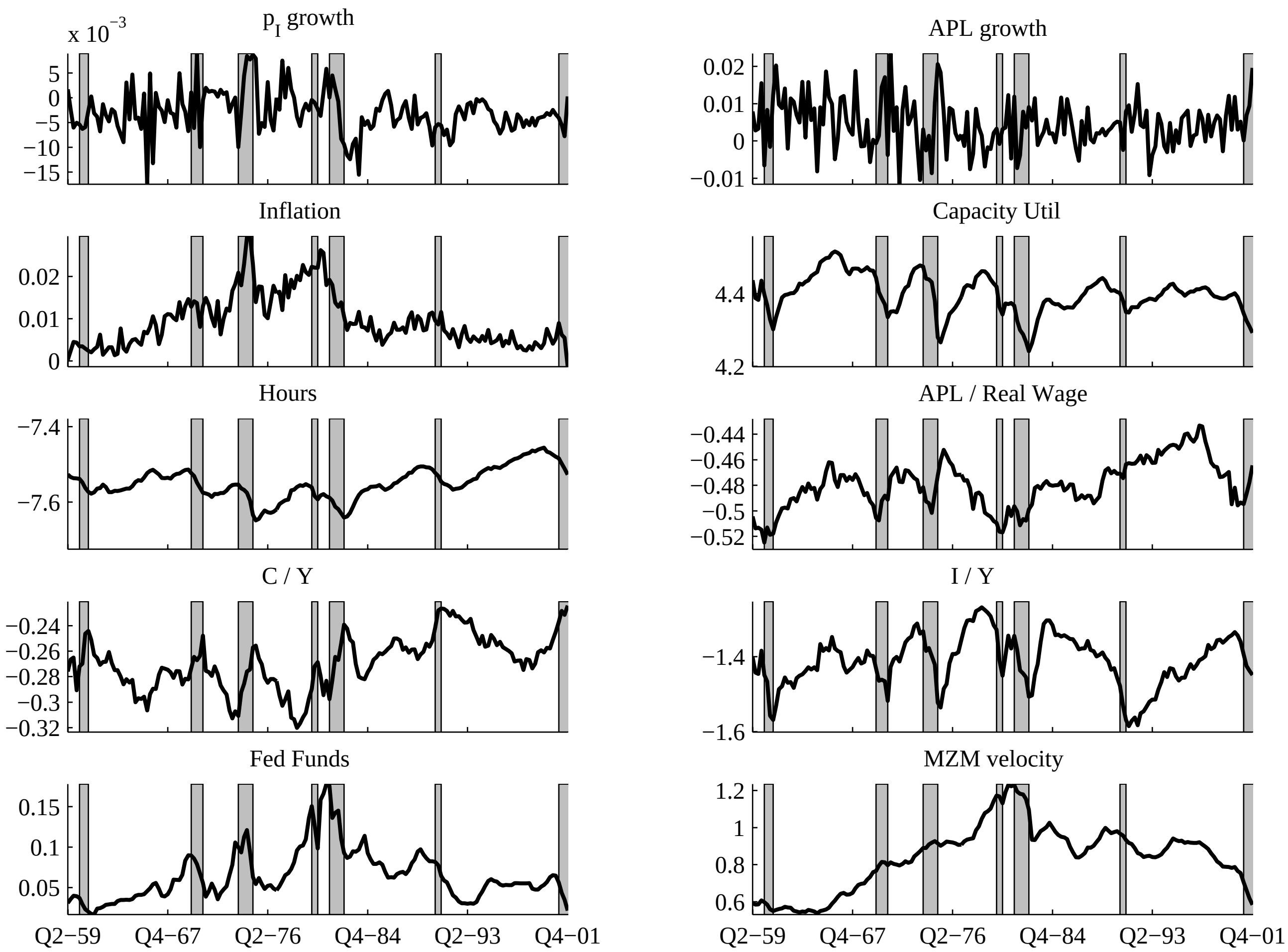


Figure 2: Log Income velocity of different monetary aggregates

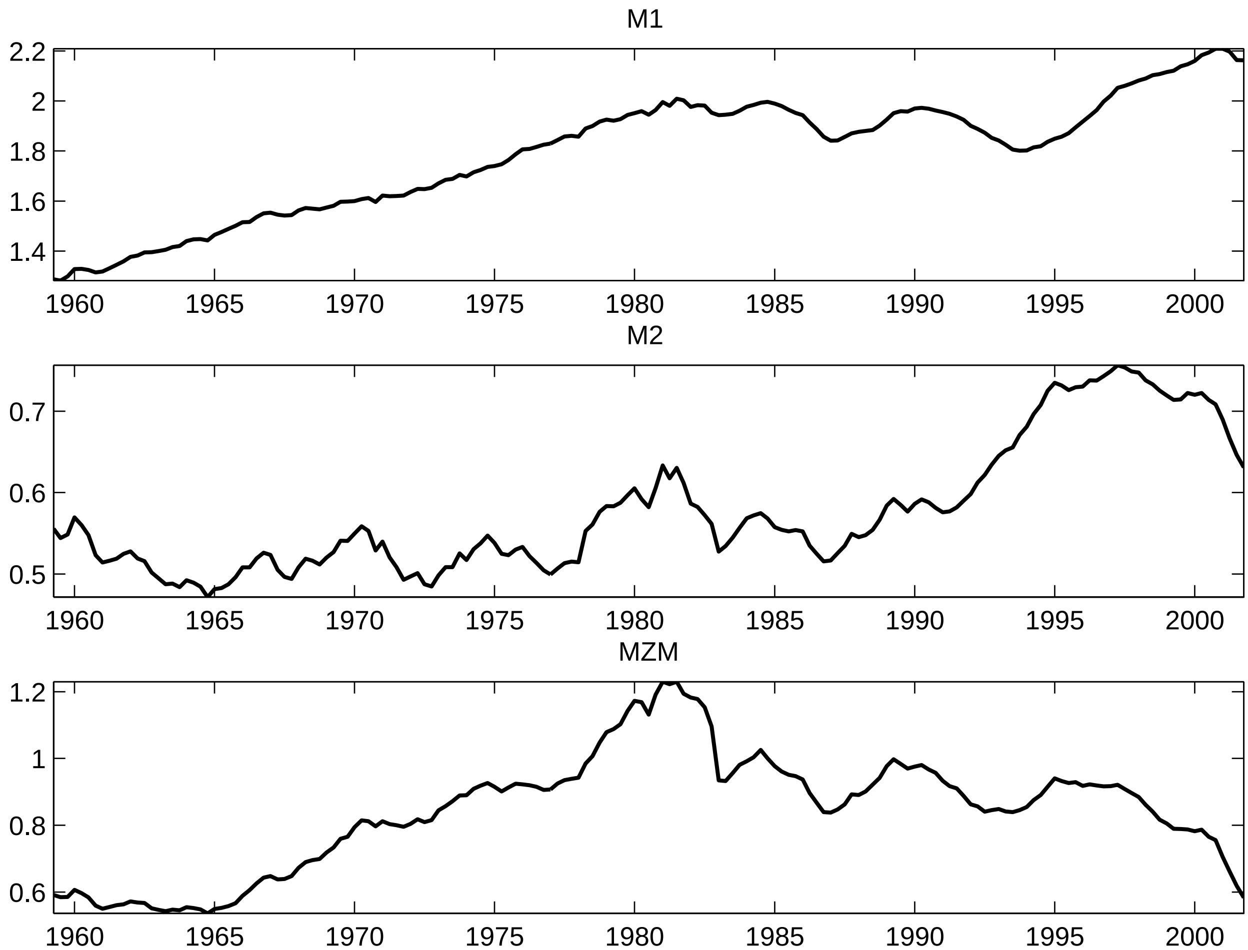


Figure 3: Benchmark model − dynamic response to a monetary policy shock

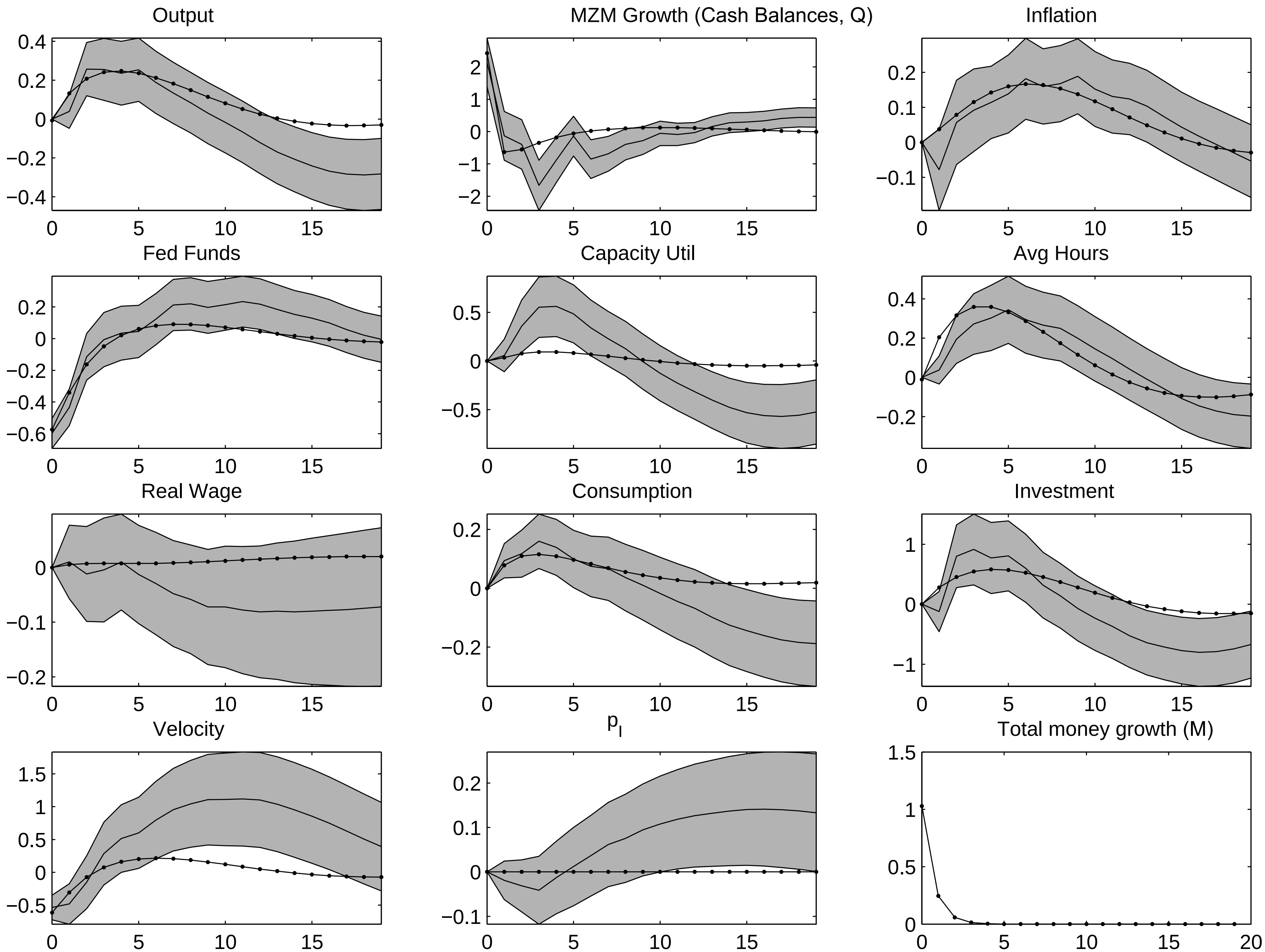


Figure 4: Benchmark model − dynamic response to a neutral technology shock

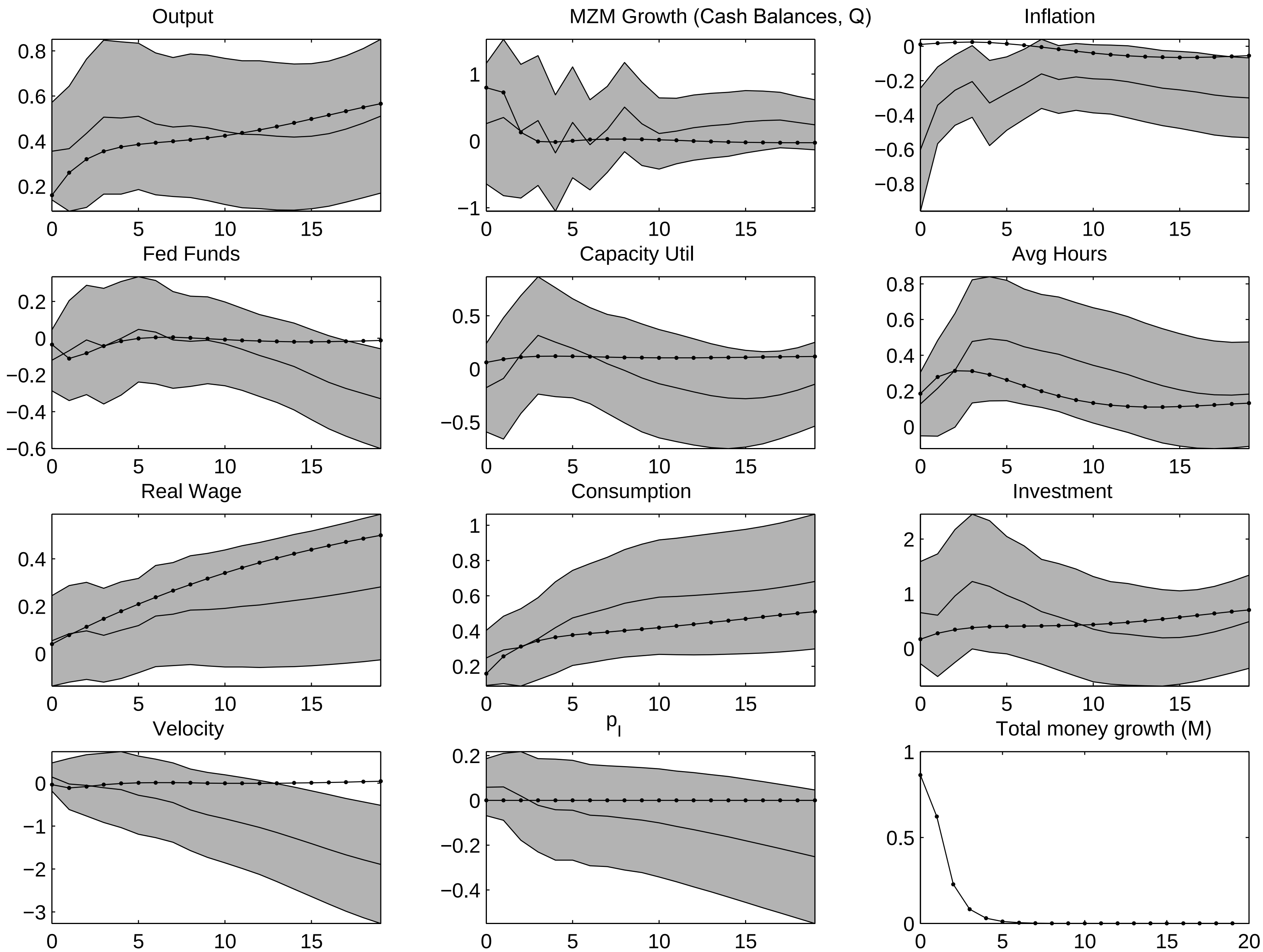


Figure 5: Benchmark model − dynamic response to an embodied technology shock

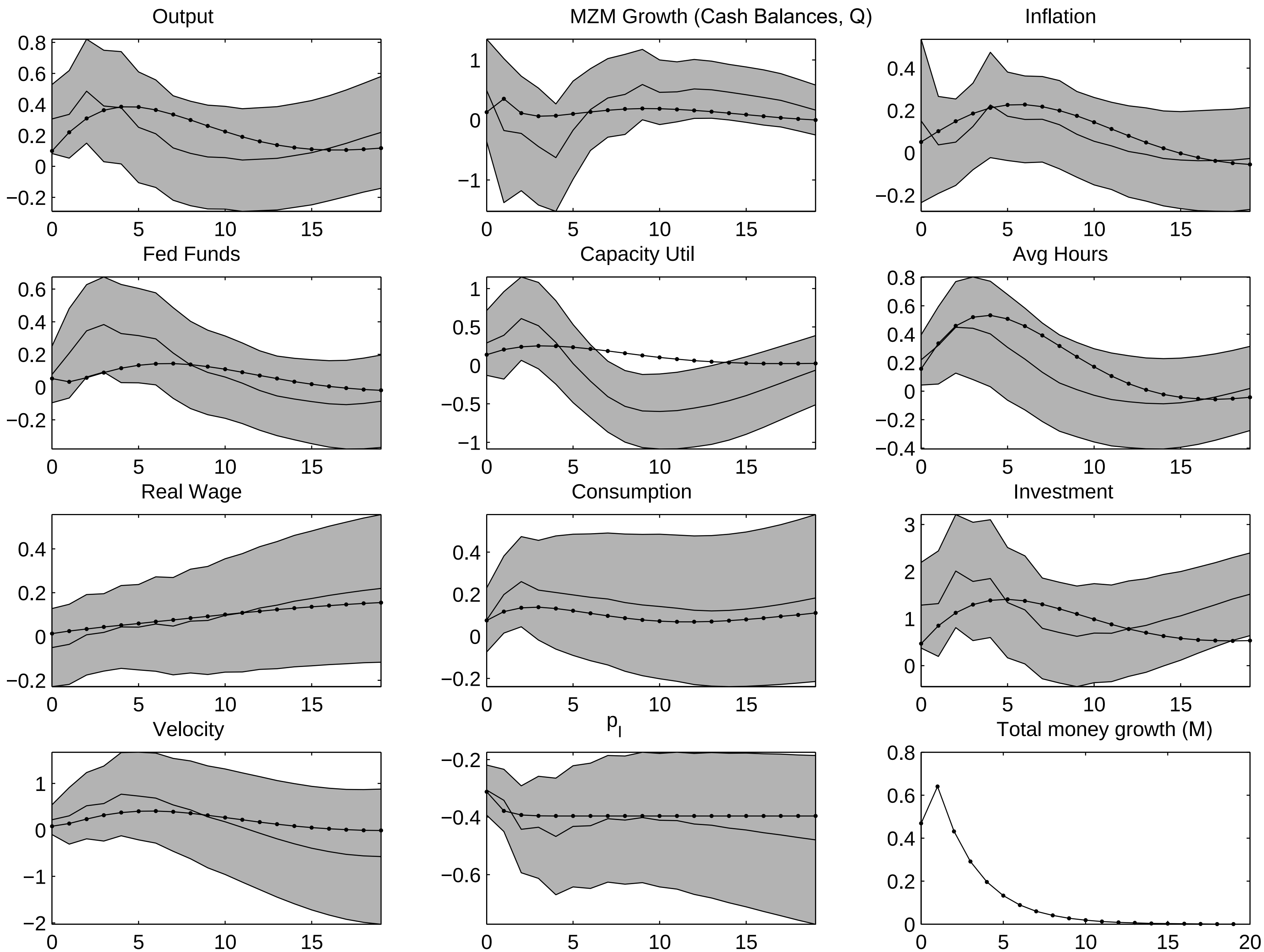


Figure 6: Historical decomposition − monetary policy shocks only

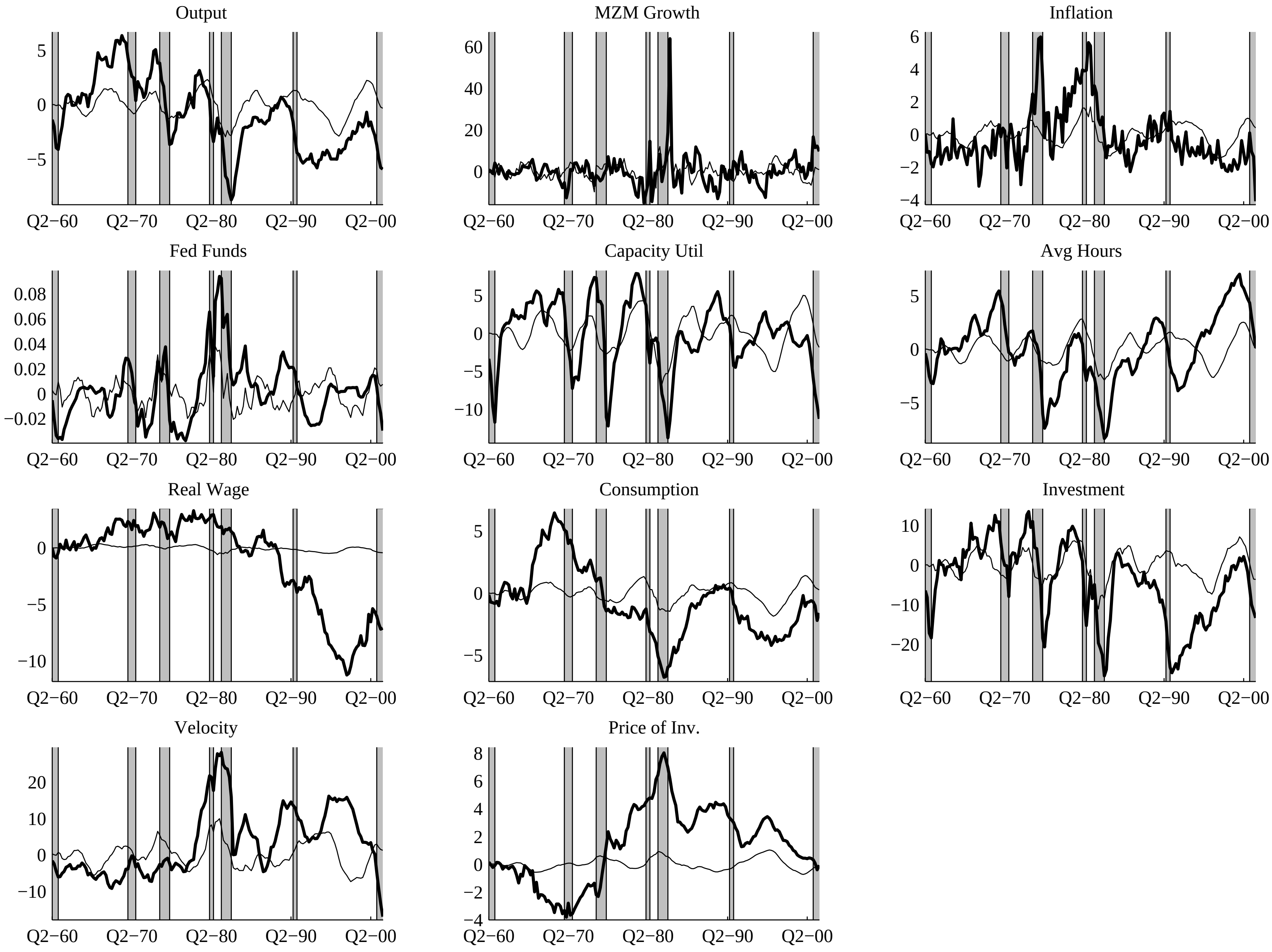


Figure 7: Historical decomposition − neutral technology shocks only

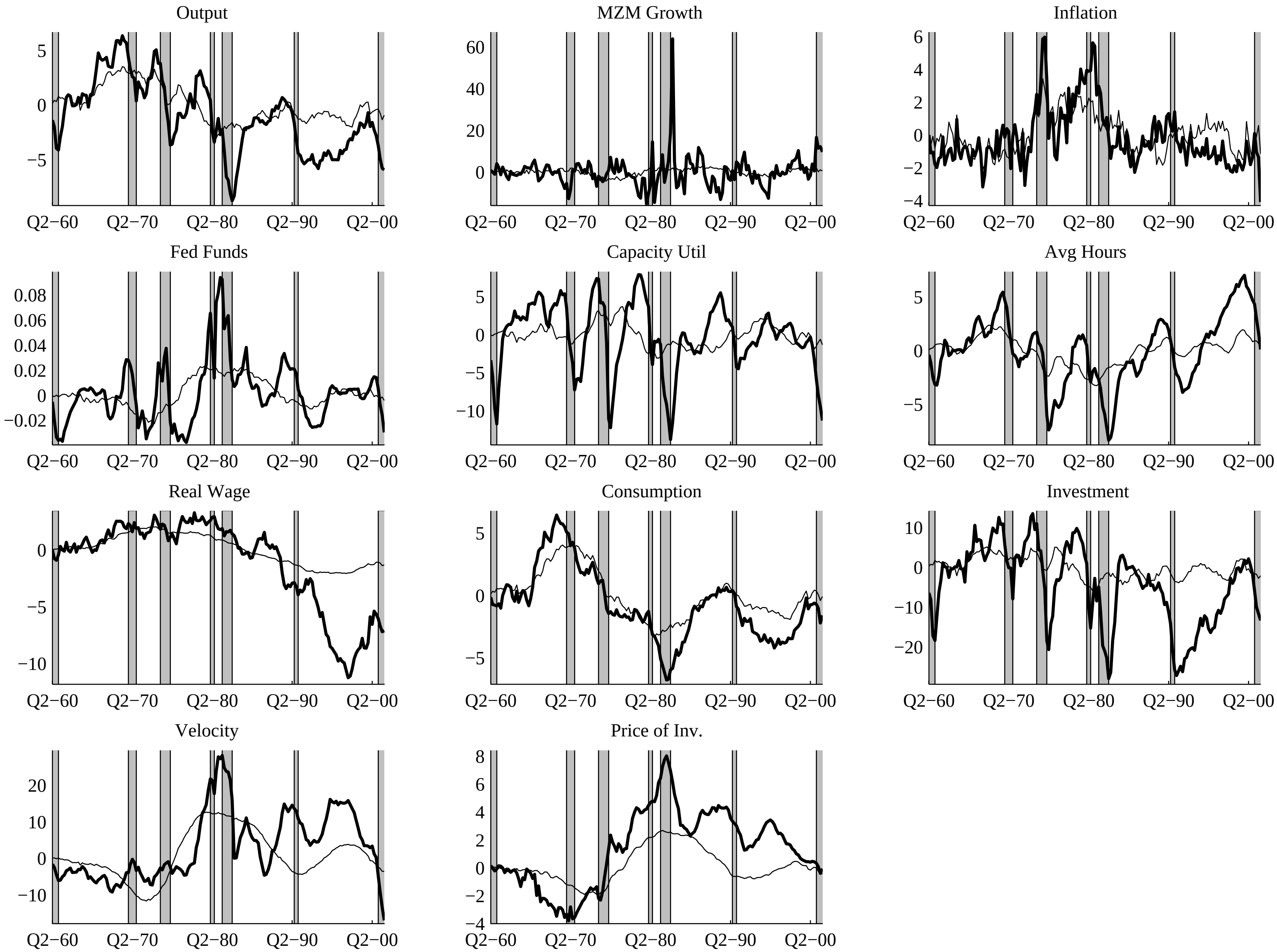


Figure 8: Historical decomposition − embodied technology shocks only

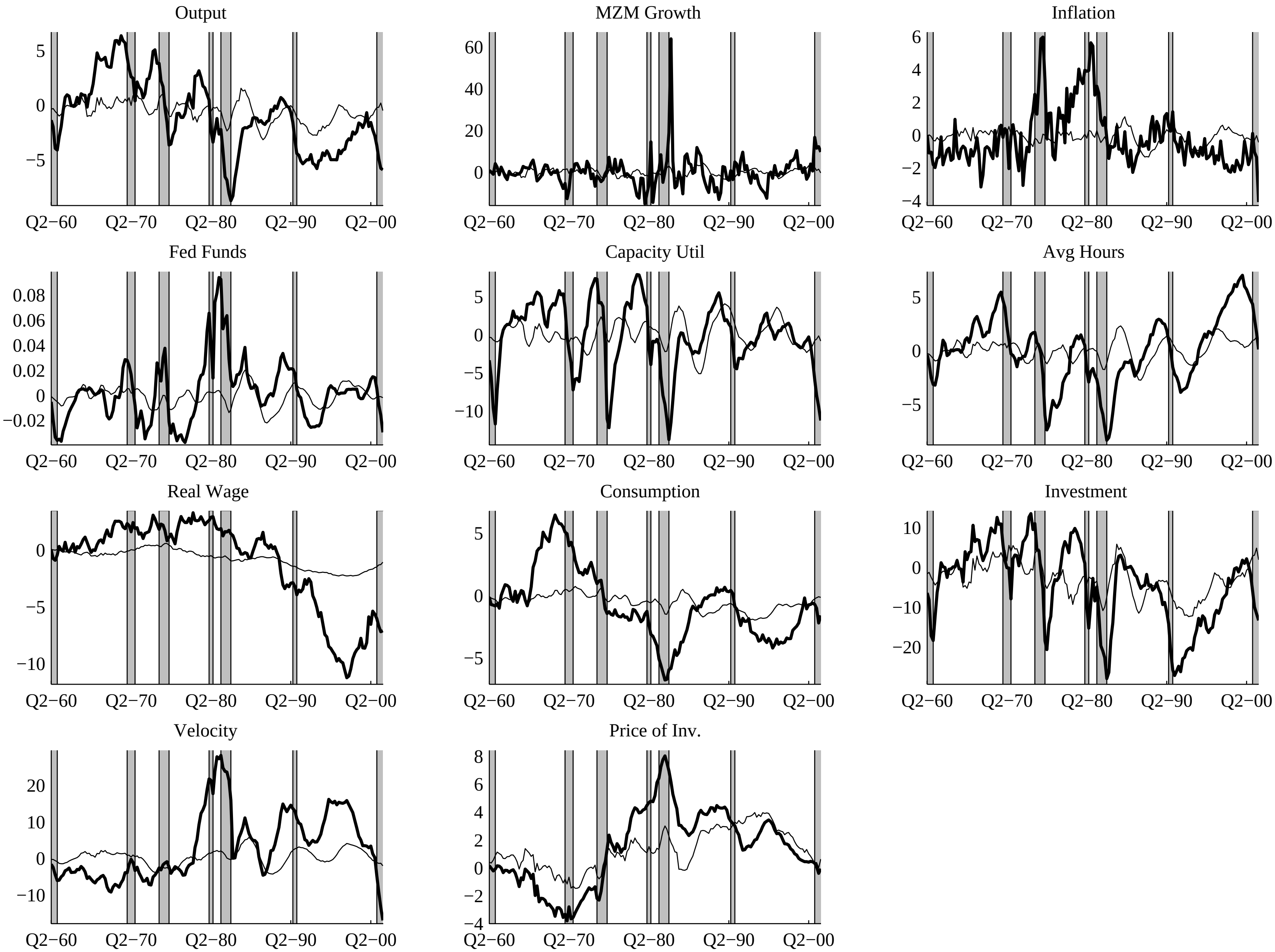


Figure 9: Historical decomposition − monetary policy and technology shocks

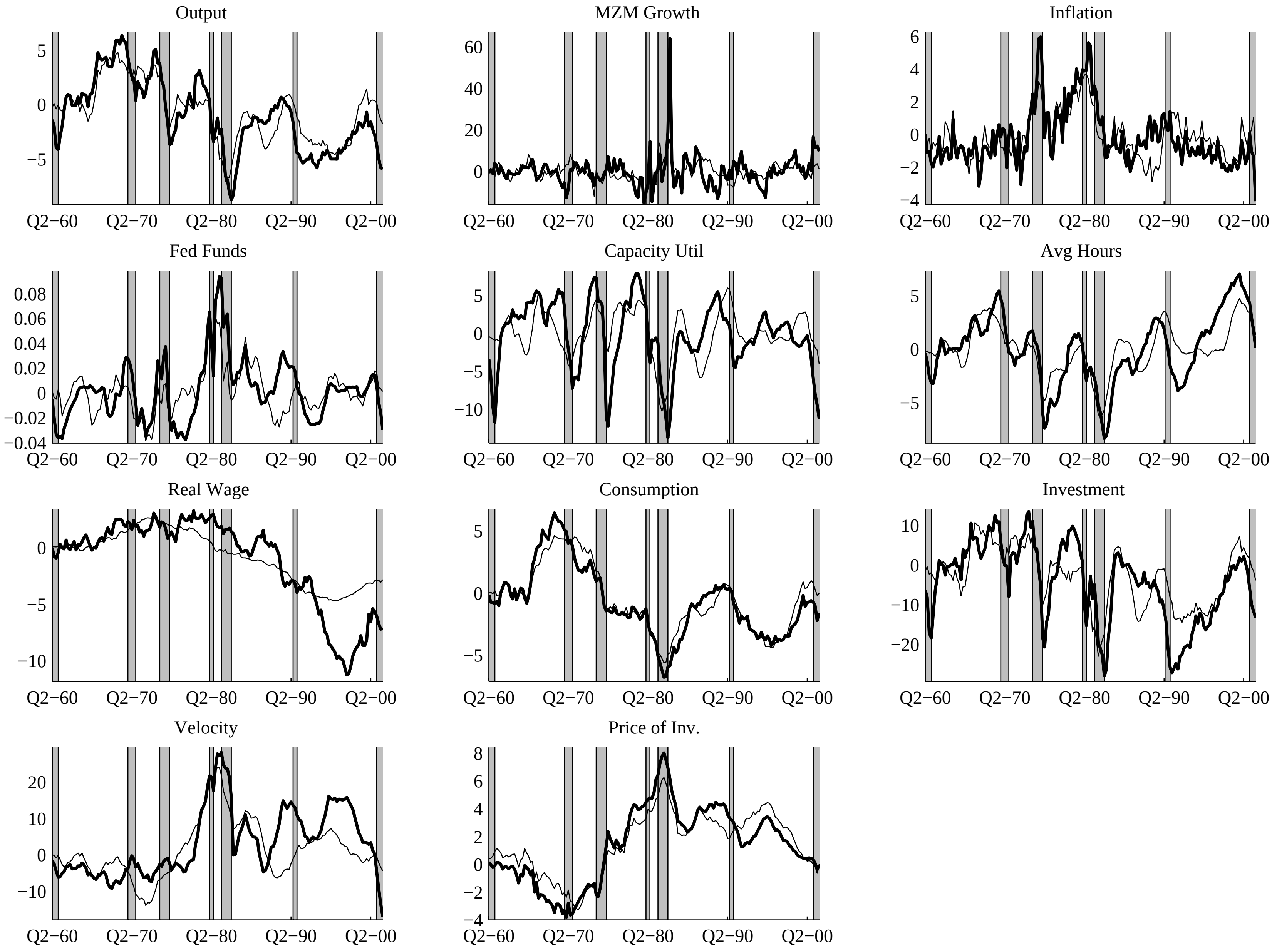


Figure 10: Model dynamic responses to a neutral technology shock with (−−) and without (−) monetary intervention

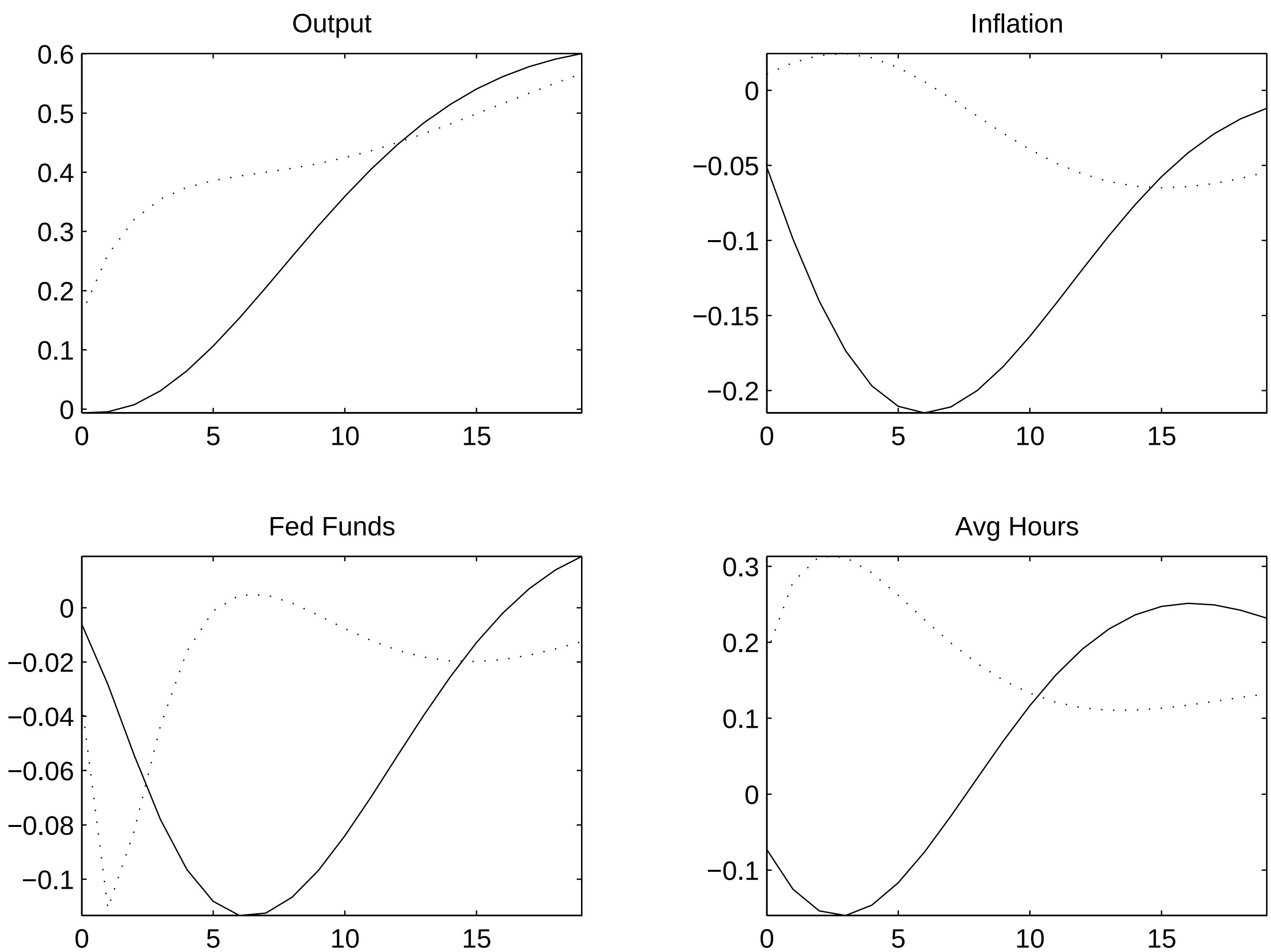


Figure 11: Model dynamic responses to an embodied technology shock with (−−) and without (−) monetary intervention

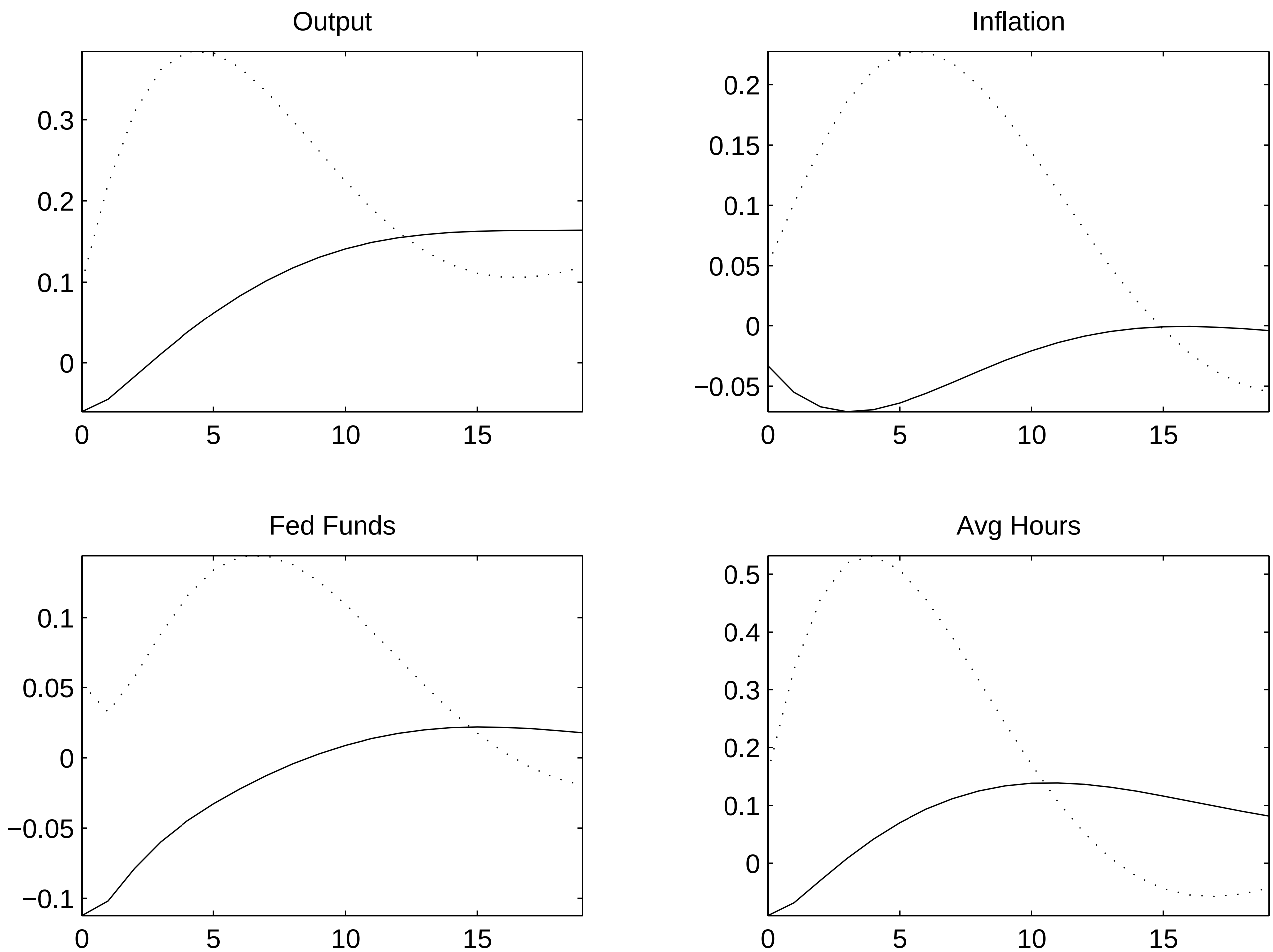


Figure 12a: Quasi First Difference of Change in Inflation Versus Log, Marginal Cost

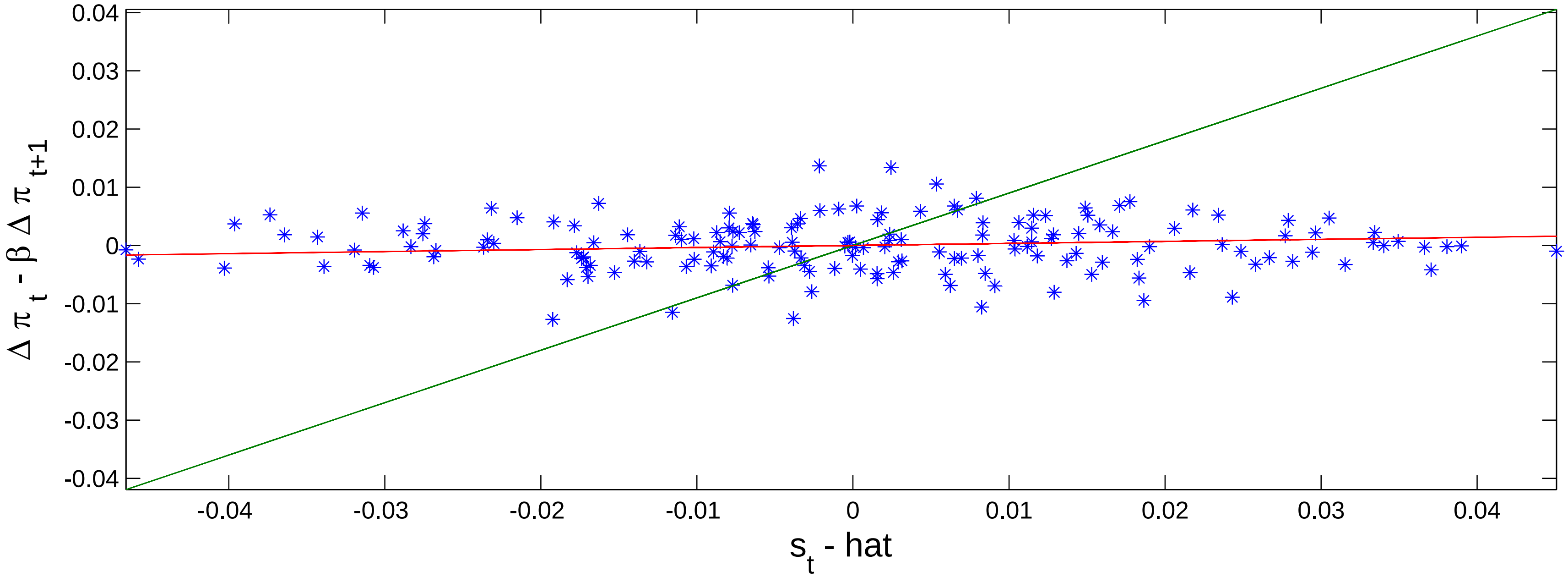


Figure 12b: Projection of Quasi First Difference of the Change in Inflation Versus Projection of Log, Marginal Cost

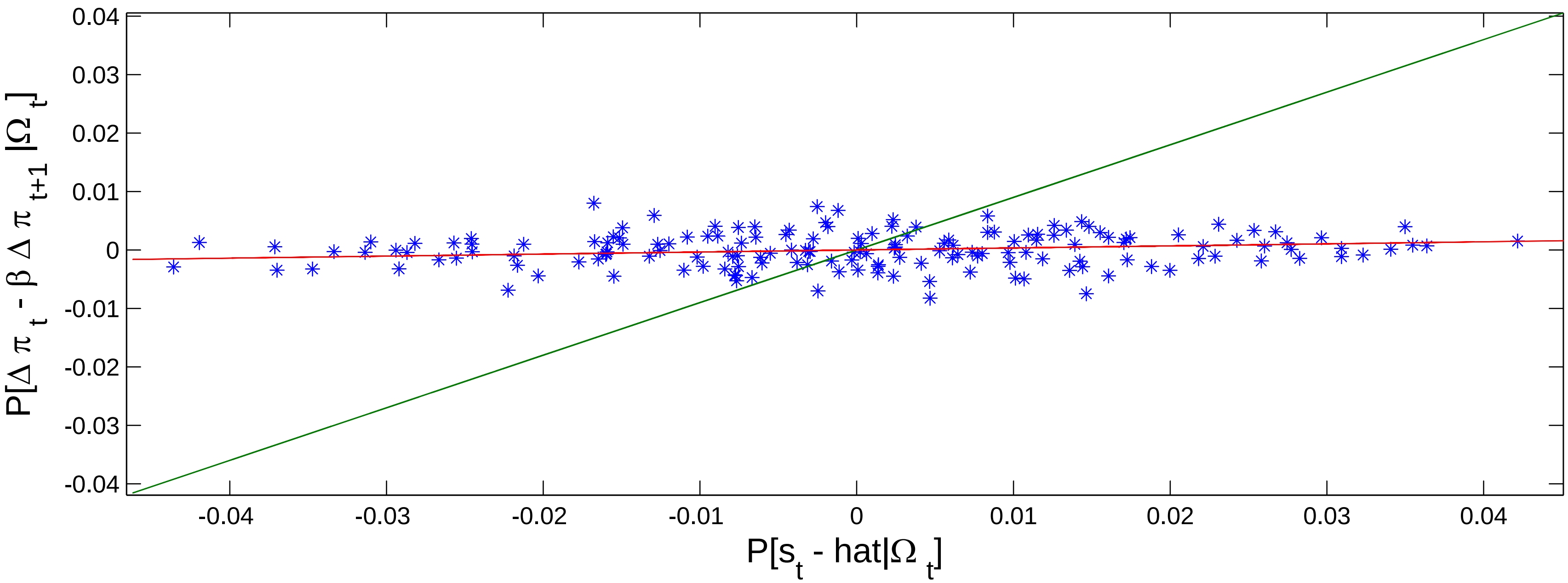


Figure 13: Firm Specificity and the Firm's Price Response to a Marginal Cost Shock

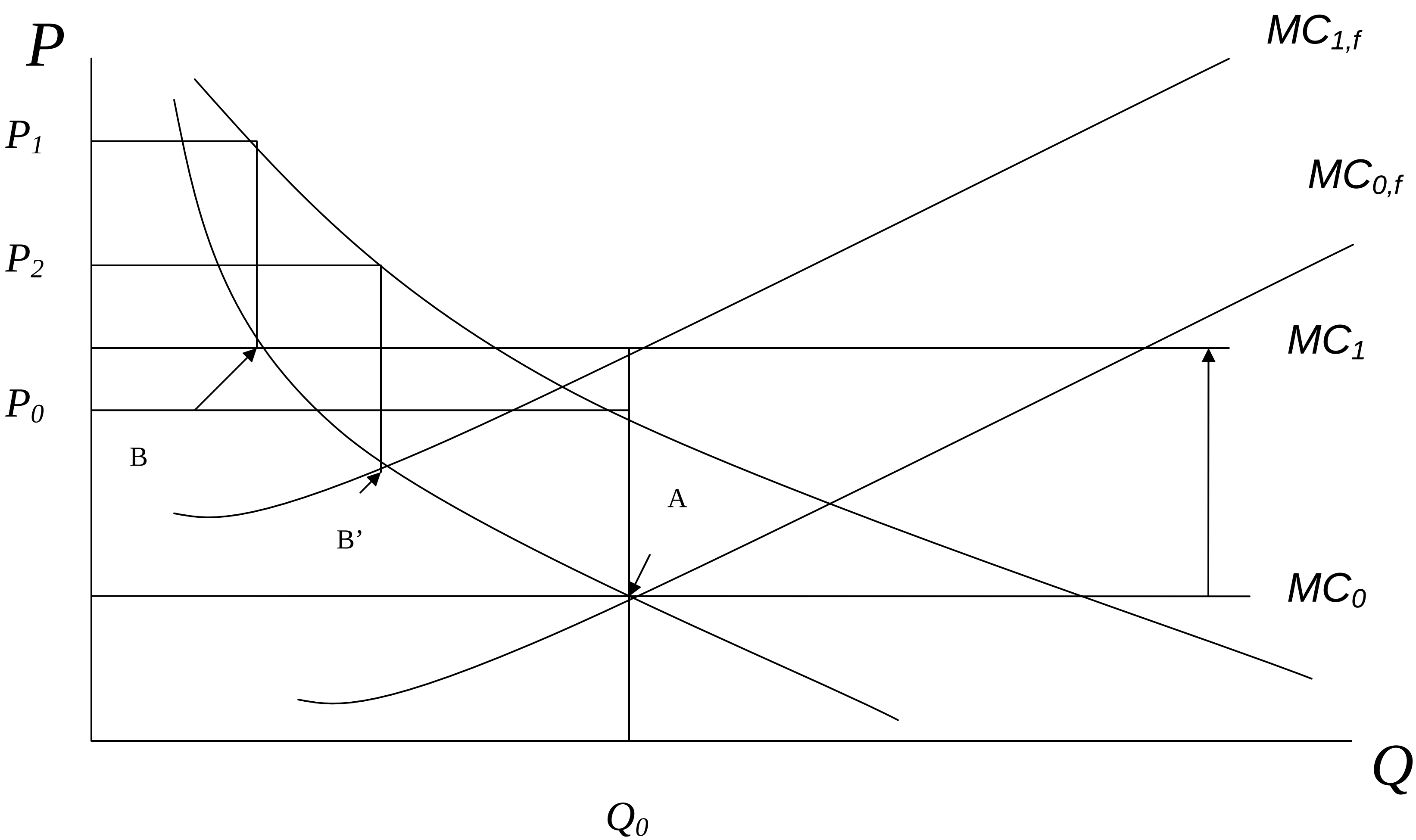


Figure 14: Features of the Distribution of Output and Prices Across Firms: Homogeneous Capital Model

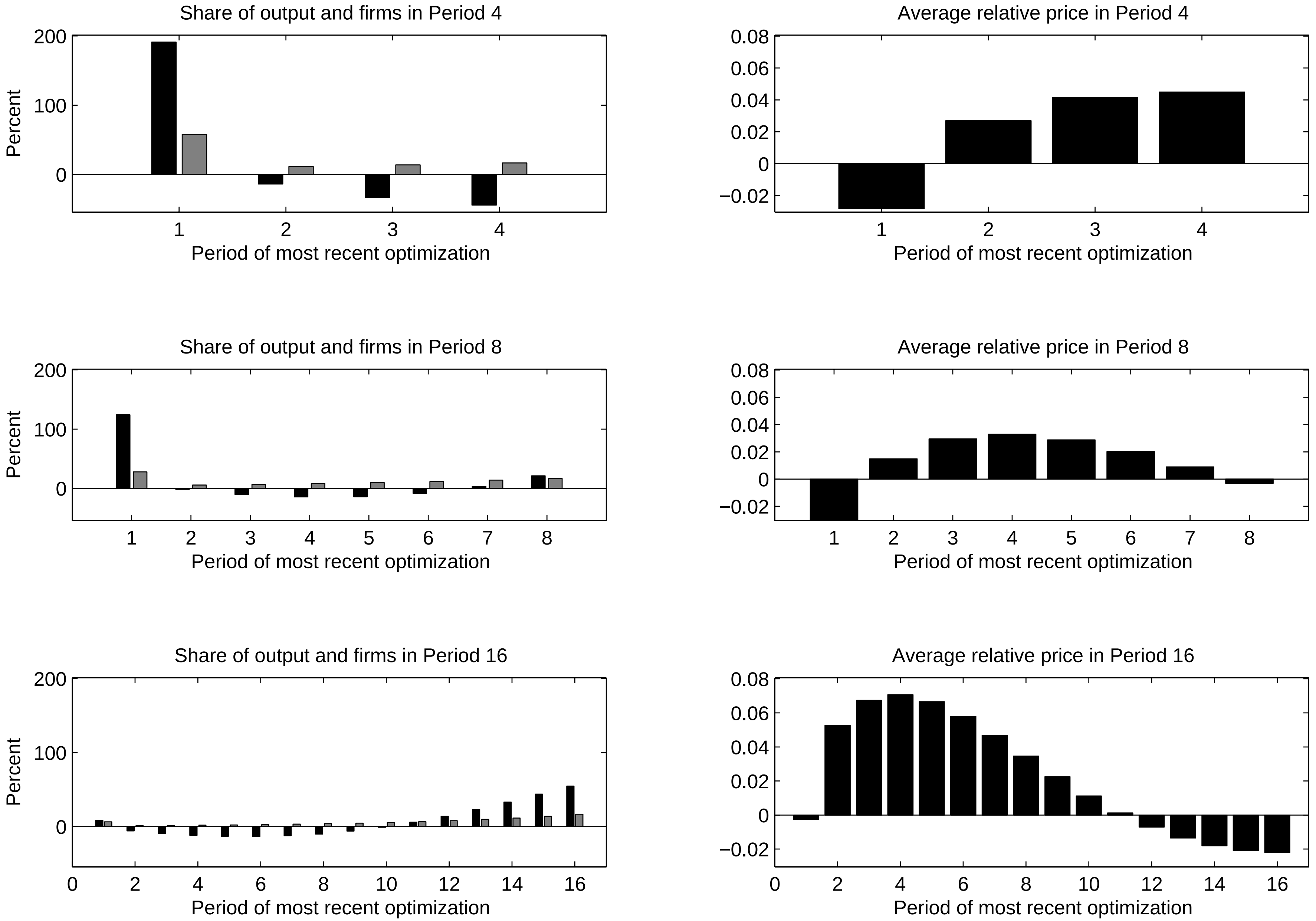
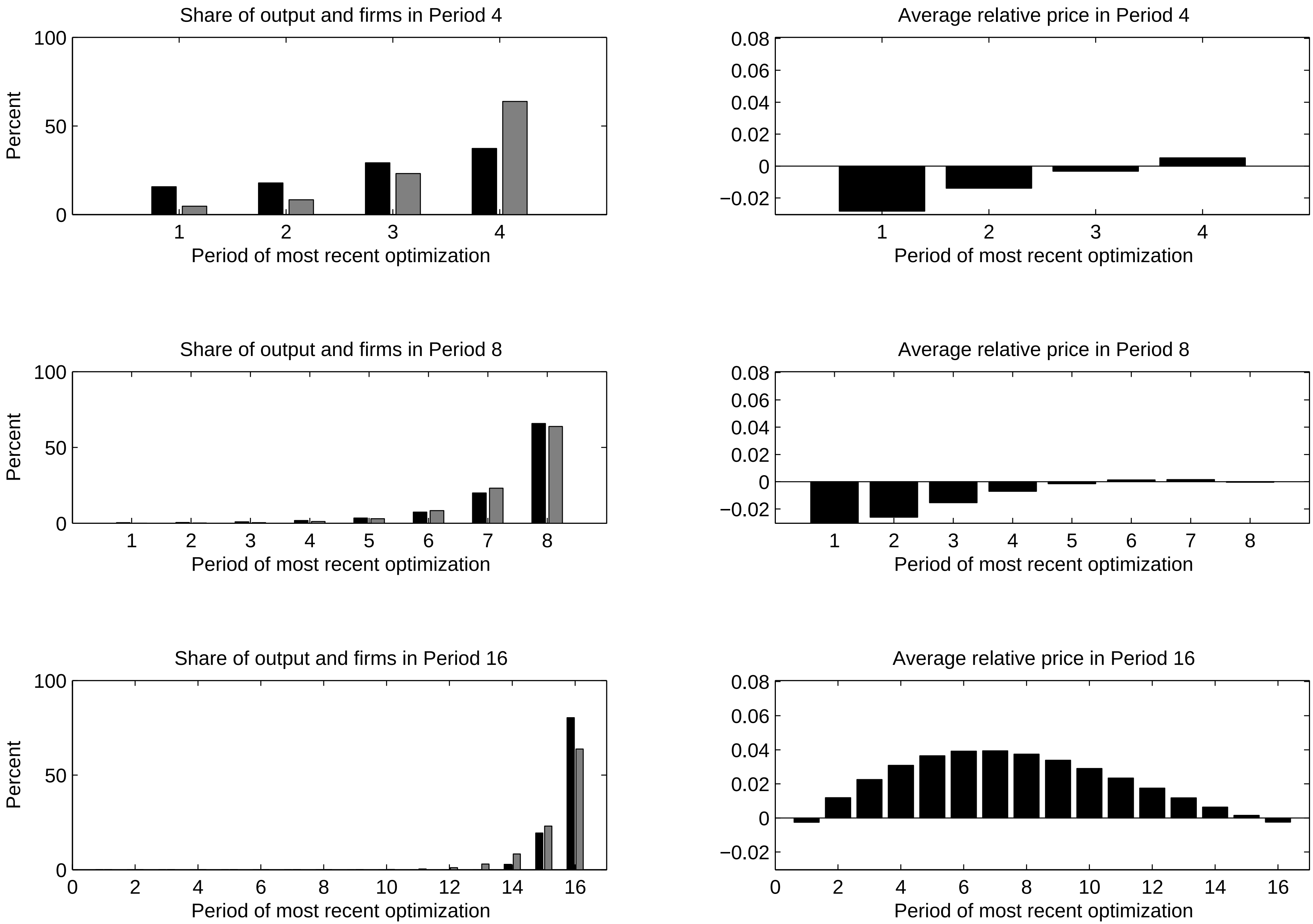
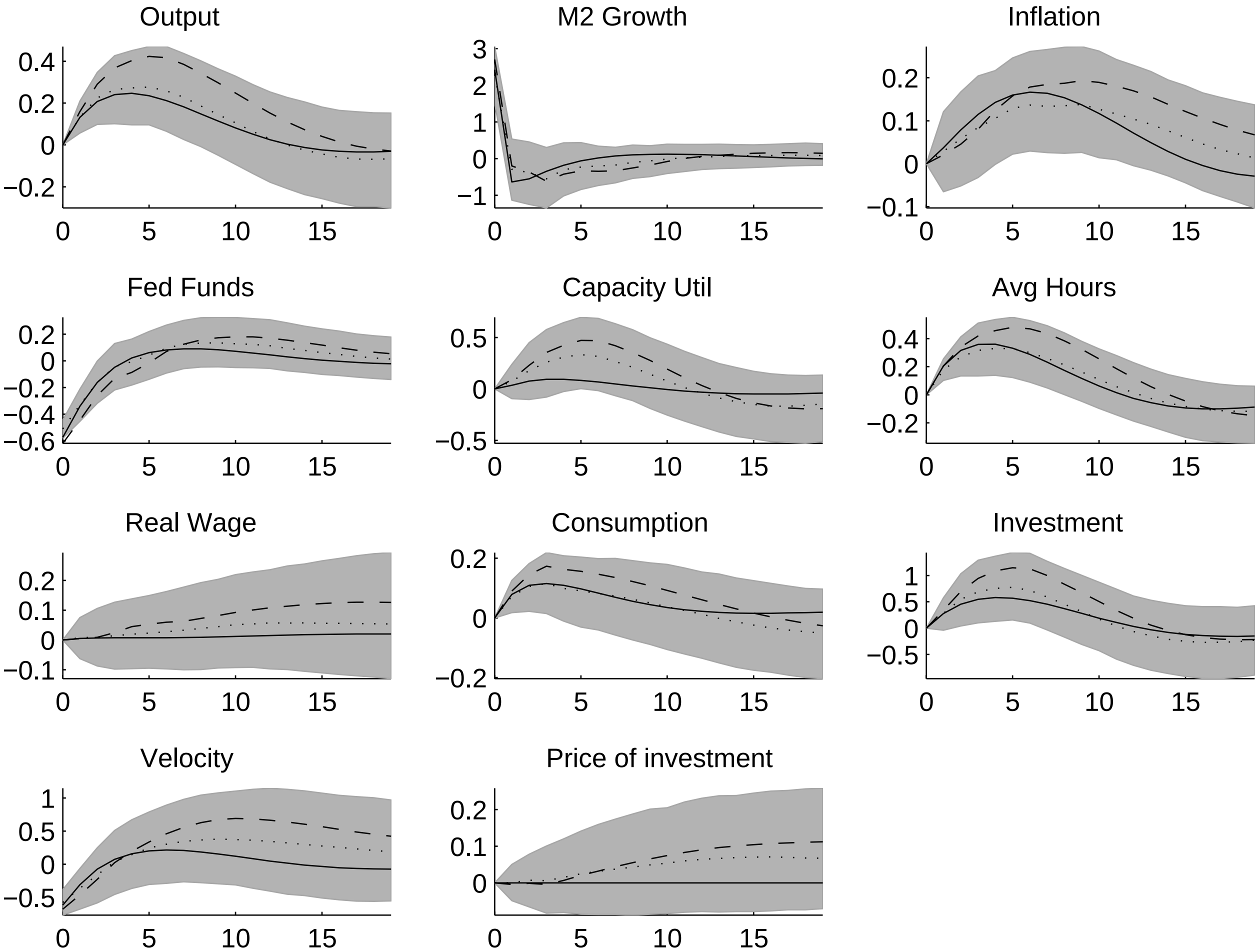


Figure 15: Features of the Distribution of Output and Prices Across Firms: Firm−specific Capital Model



4 lags in asymptotic estimated VAR

Figure 16: Monetary policy shock



4 lags in asymptotic estimated VAR

Figure 17: Investment specific technology shock

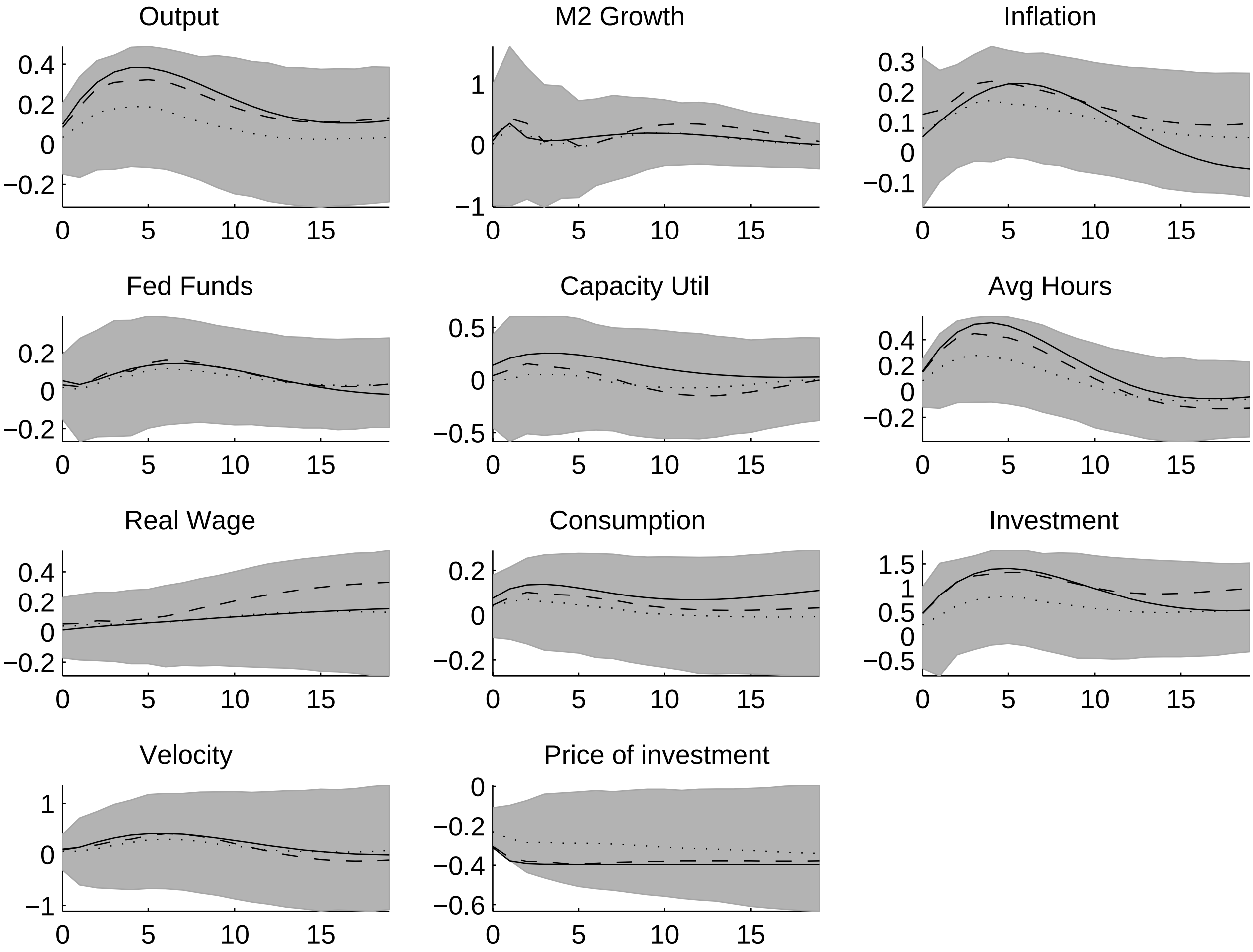


Figure 18: Neutral technology shock