

Lumpy Investment and State-Dependent Pricing in General Equilibrium*

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Abstract

The lumpy nature of plant-level investment is generally not taken into account in the context of New Keynesian monetary theory (see, e.g., Christiano et al. 2005 and Woodford 2005). We show that this is problematic. In fact, if the theory is augmented by a standard model of lumpy investment, it does not generate a realistic monetary transmission mechanism.

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1 Introduction

Many microeconomic decisions are lumpy in nature. Examples include not only infrequent price adjustment by firms but also investment decisions, durable purchases, hiring and firing decisions, inventory accumulation, and many other economic variables of interest (Caballero and Engel 2007). In the field of monetary economics, the infrequent price adjustment by firms has received special attention. The reason is simple. To the extent that prices are sticky, changes in monetary policy have consequences for the determination of real variables, at least in the short run. This transmission mechanism is generally viewed as being the hallmark of the New Keynesian (NK) theory that is widely used to analyze monetary policy (see, e.g., Woodford 2003, p. 6 and Galí 2008, p. 1).

But does NK theory really imply a quantitatively relevant monetary transmission mechanism? It is now well understood that smoothness in aggregate capital accumulation is a necessary condition for NK models to imply a reasonable monetary transmission mechanism.¹ This has motivated Christiano et al. (2005) and Woodford (2005) to introduce adjustment costs into the investment block of the NK framework,² and most of the related literature has followed their lead. But the existence of those adjustment costs make NK models inconsistent with the observed lumpiness in plant-level investment. The present paper demonstrates that this is a problematic aspect of NK theory. In fact, our results show that once an otherwise conventional NK model is augmented with a standard (S,s) investment decision, the implied monetary transmission mechanism becomes counterfactual. Specifically, the

¹The last statement regards monetary models featuring endogenous capital accumulation. An alternative way of engineering a reasonable monetary transmission mechanism is to simply assume capital accumulation away. That modeling choice is widespread in the literature. See, e.g., Galí (2008), among many others.

²Specifically, Christiano et al. (2005) assume a convex investment adjustment cost, whereas Woodford (2005) postulates a convex capital adjustment cost.

impact responses of output and investment to a monetary policy shock become unrealistically large and there is essentially no persistence in the dynamic consequences of that shock.

In a nutshell, the reason is that non-convex adjustment costs which are routinely assumed in the investment literature do not rationalize a realistic interest rate sensitivity of investment. The (S,s) nature of investment decisions is crucial to understand this result. In response to an expansionary monetary policy shock firms choose to undertake some of the investment activity that they would have otherwise done later. The front-loading implied by (S,s) investment decision making is also emphasized in House's (2008) analysis of a rich variety of RBC models featuring lumpy investment. In our context, this mechanism is important for two reasons. First, the impact investment response to the shock becomes very large. Second, the distribution of firms in the economy is altered in such a way that investment in subsequent periods is reduced. This explains both the enormous size of the impact response of investment to a monetary disturbance (which is driving the large output response) and the almost complete lack of persistence in the dynamic consequences of that shock.

These results are remarkably robust. In particular, our analysis implies that the monetary transmission mechanism becomes counterfactual regardless of the specific way in which we model the restriction on price adjustment. More concretely, we do not find a realistic monetary transmission mechanism neither under Calvo (1983) pricing nor under alternative forms of state-dependent pricing. Under the Calvo (1983) assumption the impact responses of real variables to a monetary policy shock are even larger than the corresponding outcomes under our baseline state-dependent pricing model and there is essentially no gain in terms of persistence. We also show that the price adjustment cost can be specified in such a way that the impact re-

sponses of the real variables are reduced with respect to the corresponding outcomes under our baseline calibration. However, the resulting version of our model still fails to generate persistent effects of monetary policy shocks or a realistic split of output between investment and consumption. The difference in results implied by the different forms of (S,s) pricing and the Calvo mechanism is a consequence of an extensive margin effect à la Caballero and Engle (2007). We also change various other aspects of our baseline calibration. In each case we find that an empirically relevant monetary transmission mechanism cannot be entertained as long as our model features a realistic degree of lumpiness in investment.

Given the large size of the literature on the monetary transmission mechanism one might wonder why our main result has not been uncovered before. One important reason is that the general equilibrium consequences of joint decision making at the firm level cannot easily be computed. This explains why most papers so far have focused on one particular lumpy decision at a time. For instance, Thomas (2002), Gourio and Kashyap (2007), Bachmann et al. (2008) and Khan and Thomas (2008) analyze aggregate consequences of lumpy investment in the context of RBC models, whereas Dotsey et al. (1999), Dotsey and King (2005), Bakhshi et al. (2007), Golosov and Lucas (2007), Gertler and Leahy (2008), Nakamura and Steinsson (2008), Dotsey et al. (2009) and Midrigan (2011) focus exclusively on the role of price rigidity for aggregate dynamics. We overcome those difficulties by using the method developed in Reiter (2009, 2010).

To our best knowledge there are only two other papers that have asked questions which are closely related to the ones that motivate our work.³ First, Sveen and Weinke (2007) have modeled joint time-dependent pricing and investment decisions.

³Less related to the focus of the present paper, Kryvtsov and Midrigan (2009) integrate pricing and inventory decisions in the context of a menu cost model. They use their model to analyze the behavior of inventories in the aftermath of monetary policy shocks.

The preferred calibration advocated in that paper implies a reasonable monetary transmission mechanism in the presence of infrequent investment at the firm level.⁴ This is an interesting result, but the assumption of a time-dependent investment rule is in stark contrast to the choices that are typically made in investment theory. This has motivated us to revisit the monetary transmission mechanism in the presence of lumpy investment. We find that it is important to realize how drastically the results in Sveen and Weinke (2007) change in the presence of a standard (S,s) investment decision.

Second, Johnston (2009) has also investigated the effect of monetary shocks in a framework that integrates (S,s) pricing and investment decisions in general equilibrium. He arrives at conclusions that appear to contradict ours. In his model, the presence of lumpy investment lowers somewhat the persistence in the real consequences of monetary disturbances (compared to a model with a convex capital adjustment cost), but has otherwise no dramatic consequences. In our model, lumpy investment destroys the monetary transmission mechanism as we know it. Where does this discrepancy in results come from? There are three key differences with respect to our framework. First, Johnston (2009) ensures tractability of his model by making assumptions which limit the extent to which the timing of pricing decisions is chosen optimally. Second, he assumes the quantity equation according to which real money balances, $\frac{M_t}{P_t}$, are equal to aggregate real output, Y_t , or, equivalently, $M_t = Y_t P_t$. Third, his specification of monetary policy takes the form of a money growth rule. But given the quantity equation exogenous money growth combined with a sufficiently strong restriction on price adjustment must enforce some smoothness in aggregate real output. Indeed, by assuming the quantity equation as

⁴Specifically, Sveen and Weinke (2007) obtain the following equivalence result. If pricing and lumpy investment decisions are made in a time-dependent fashion, then the model is observationally equivalent in the aggregate to a model of convex capital adjustment costs at the firm-level à la Woodford (2005).

well as a money growth rule in the context of our framework we can engineer a good looking monetary transmission mechanism if the restriction on price adjustment is strong enough. Specifically, by deviating from our maintained assumptions in this way, we obtain results in the spirit of Johnston (2009) under Calvo pricing whereas the monetary transmission mechanism is still counterfactual in the presence of a state-dependent pricing decision. It is therefore important to realize that the results in Johnston (2009) are largely due to a smoothing mechanism which is absent in our model. The reason is that we follow the current mainstream approach of modeling the monetary transmission mechanism, where the central bank uses the short term nominal interest rate as its policy instrument.

The remainder of the paper is organized as follows. Section 2 outlines the model. Section 3 presents the results and Section 4 concludes.

2 The Model

2.1 Households

Households are assumed to have access to a complete set of financial markets. The representative household has the following period utility function

$$U(C_t, L_t) = \ln C_t + \frac{\eta}{1 - \phi} (1 - L_t)^{1 - \phi}, \quad (1)$$

which is separable in its two arguments C_t and L_t . The former denotes a Dixit-Stiglitz consumption aggregate while the latter is meant to indicate hours worked. Our notation reflects that a household's time endowment is normalized to one per period and throughout the analysis the subscript t denotes the time period. The inverse of the steady state labor supply elasticity is given by $\frac{\phi L}{1 - L}$ and we adopt

the convention that a variable without time subscript indicates its steady state value. Parameter η is a scaling parameter whose role will be discussed below. The consumption aggregate reads

$$C_t \equiv \left(\int_0^1 C_t(i)^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}}, \quad (2)$$

where ϵ is the elasticity of substitution between different varieties of goods $C_t(i)$. The associated price index is defined as follows

$$P_t \equiv \left(\int_0^1 P_t(i)^{1-\epsilon} di \right)^{\frac{1}{1-\epsilon}}, \quad (3)$$

where $P_t(i)$ is the price of good i . Requiring optimal allocation of any spending on the available goods implies that consumption expenditure can be written as $P_t C_t$. Households are assumed to maximize expected discounted utility

$$E_t \sum_{k=0}^{\infty} \beta^k U(C_{t+k}, L_{t+k}),$$

where β is the subjective discount factor. The maximization is subject to a sequence of budget constraints of the form

$$P_t C_t + E_t \{Q_{t,t+1} D_{t+1}\} \leq D_t + P_t W_t L_t + T_t, \quad (4)$$

where $Q_{t,t+1}$ denotes the stochastic discount factor for random nominal payments and D_{t+1} gives the nominal payoff associated with the portfolio held at the end of period t . We have also used the notation W_t for the real wage and T_t is nominal dividend income resulting from ownership of firms.

The labor supply equation implied by this structure takes the standard form

$$\eta C_t (1 - L_t)^{-\phi} = W_t, \quad (5)$$

and the consumer Euler equation is given by

$$Q_{t,t+1}^R = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-1}, \quad (6)$$

where $Q_{t,t+1}^R \equiv Q_{t,t+1} \Pi_{t+1}$ is the real stochastic discount factor, and $\Pi_{t+1} \equiv \frac{P_{t+1}}{P_t}$ is the gross rate of inflation between periods t and $t+1$. We also note that $E_t \{Q_{t,t+1}\} = R_t^{-1}$, where R_t is the gross risk free nominal interest rate.

2.2 Firms

There is a continuum of firms and each of them is the monopolistically competitive producer of a differentiated good. Each firm $i \in [0, 1]$ is assumed to maximize its market value subject to constraints implied by the demand for its good and the production technology it has access to.⁵ Moreover each firm faces random fixed costs of price and capital adjustment. This implies generalized (S, s) rules for price-setting and for investment. The central question of the present paper regards the monetary transmission mechanism. Monetary policy shocks are therefore the only source of aggregate uncertainty that we consider here. In each period the time line is as follows.

1. The cost of adjusting the price as well as the monetary policy shock realize.
2. The firm changes its price (or not).

⁵There is no distinction between a plant and a firm in the context of our model and we therefore use both terms interchangeably.

3. Production takes place.
4. The cost of adjusting the capital stock realizes.
5. The firm invests (or not).

Let us now be more specific about the above mentioned constraints. Each firm i has access to the following Cobb-Douglas production function

$$Y_t(i) = L_t(i)^{\alpha_L} K_t(i)^{\alpha_K}, \quad (7)$$

where α_L and α_K denote the shares of labor and capital in production. In order to invest or to change its price a firm must pay a fixed cost. More precisely, we denote the cost functions for investment and for price-setting by $C_{k,t}(i)$ and $C_{p,t}(i)$. They are both measured in units of the aggregate good and are given by

$$C_{k,t}(K_t(i), K_{t+1}(i), c_k) = \begin{cases} 0 & \text{if } K_{t+1}(i) = (1 - \chi\delta) K_t(i), \\ c_k & \text{otherwise.} \end{cases} \quad (8)$$

$$C_{p,t}(P_t(i), P_{t+1}(i), c_p) = \begin{cases} 0 & \text{if } P_{t+1}(i) = P_t(i), \\ c_p & \text{otherwise.} \end{cases} \quad (9)$$

The realizations of the capital and price adjustment costs are denoted c_k and c_p , respectively, and δ is the rate of depreciation. We follow Bachmann et al. (2006) in assuming that the effective depreciation rate is $\chi\delta$, where parameter $\chi \in [0, 1]$ is used to model the extent to which firms are assumed to conduct maintenance investment for which no adjustment cost is incurred. This way, we capture the empirical fact that firms need to do some small investments to keep their machines running. For the price adjustment cost we follow Dotsey et al. (1999) in assuming an inverted

S-shaped distribution, whereas we assume a linear distribution function for capital adjustment costs, as in Thomas (2002) and Khan and Thomas (2008).

Cost-minimization on the part of households and firms implies that demand for good i is given by

$$Y_t^d(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} Y_t^d, \quad (10)$$

where aggregate demand is $Y_t^d = C_t + I_t + C_{p,t}$, which consists of consumption, C_t , aggregate investment, $I_t \equiv \int_0^1 [K_{t+1}(i) - (1 - \delta) K_t(i) + C_{k,t}(i)] di$, and aggregate price-setting costs, $C_{p,t} \equiv \int_0^1 C_{p,t}(i) di$. Each firm maximizes

$$E_t \sum_{j=0}^{\infty} Q_{t,t+j}^R \{ \Psi_{t+j}(i) - [K_{t+j+1}(i) - (1 - \delta) K_{t+j}(i)] - C_{k,t+j}(i) - C_{p,t+j}(i) - \zeta W_{t+j} \},$$

where $\Psi_t(i) \equiv \frac{P_t(i)}{P_t} Y_t(i) - W_t L(i)$ is the gross operating surplus, and ζ denotes a fixed cost which is measured in units of labor and whose role will be explained when we discuss our calibration. The maximization is subject to the constraints in equations (7), (8), (9) and (10).

2.3 Market Clearing and Monetary Policy

The goods market clearing condition reads

$$Y_t(i) = Y_t^d(i) \text{ for all } i. \quad (11)$$

Clearing of the labor market requires

$$\int_0^1 [L_t(i) + \zeta] di = L_t. \quad (12)$$

To close the model we assume a Taylor-type rule for the conduct of monetary policy

$$R_t = (R_{t-1})^{\phi_r} \left[\frac{\Pi}{\beta} \left(\frac{\Pi_t}{\Pi} \right)^{\phi_\pi} \left(\frac{Y_t}{Y} \right)^{\phi_y} \right]^{1-\phi_r} e^{e_{r,t}}. \quad (13)$$

Parameters ϕ_π and ϕ_y indicate the long-run responsiveness of the nominal interest rate to changes in current inflation and output,⁶ respectively, and parameter ϕ_r measures interest rate smoothing. The shock, $e_{r,t}$, is *i.i.d.* with zero mean.

2.4 Baseline Calibration

We consider a quarterly model. The discount factor, β , is set to 0.99, which implies an annualized steady state real interest rate of about 4 percent. Annualized steady state inflation is set to 2 percent. Parameter η is set to imply that households spend one-third of their available time working. Combined with $\phi = 2$ this implies a unit labor supply elasticity in the steady state. We follow Golosov and Lucas (2007) in assuming a value of 7 for the elasticity of substitution between different varieties of goods, ϵ , which implies a desired frictionless markup of about 20 percent. Cooper and Haltiwanger (2006) estimate the curvature in the relationship between a firm's period profit and its capital stock. We therefore impose that the concavity of the profit function in a frictionless version of our model⁷ is 0.592, which is in line with

⁶Usually, the output gap, i.e., the ratio between equilibrium output and natural output (defined as the equilibrium output under flexible prices) enters the specification of monetary policy. Notice, however, that natural output does not change in response to a monetary disturbance.

⁷Consider a firm's gross operating surplus, $\Psi(i)$, in the flexible-price counterpart of our model. Invoking the demand function combined with the production function, we can write:

$$\Psi(K(i)) = \max_{L(i)} \left\{ [K(i)^{\alpha_K} L(i)^{\alpha_L}]^{\frac{1}{\nu}} Y^{1-\frac{1}{\nu}} - WL(i) \right\}.$$

where $\nu \equiv \epsilon/(\epsilon - 1)$. Using the first-order condition to substitute for $L(i)$ gives

$$\Psi(K(i)) = \Xi K(i)^\Theta,$$

where Ξ is a constant and $\Theta \equiv \frac{\alpha_K}{\nu - \alpha_L}$ is the curvature estimated in Cooper and Haltiwanger (2006).

their estimate. We also require that our model implies a labor share of 0.64 and a yearly capital-to-output ratio of 2.352 (see, e.g., Khan and Thomas 2008). The last three empirical values are targeted by our choice of the technology parameters α_L and α_K as well as the fixed cost ζ . The rate of depreciation is set to $\delta = 0.025$ which implies a steady state investment to capital ratio of 10 percent a year. We allow for 33 percent maintenance, i.e., we set χ to $1/3$. This value is in line with the empirical evidence reported in Bachmann et al. (2006) and the references therein.

The parameters of the cost distribution functions are set such that our model is in line with the following micro evidence. Each quarter about 25 percent of firms change their price (see, e.g., Aucremanne and Dhyne 2004, Baudry et al. 2004, and Nakamura and Steinsson 2008) and each year about 18 percent of firms make lumpy investments (i.e., $I/K > 20$ percent). Those investments account for about 50 percent of aggregate investment (see, e.g., Khan and Thomas 2008). For prices, we follow Dotsey et al. (1999) and assume a cost distribution function of the form $G(\xi) = c_1 + c_2 \tan(c_3\xi - c_4)$, which is parametrized by c_1 , c_2 , c_3 and c_4 . We set $c_3 = 438.4/B_p$ and $c_4 = 1.26$ where $B_p = 0.00467$. Parameters c_1 and c_2 are set such that $G(0) = 0$ and $G(B_p) = 1$. For capital adjustment costs, the distribution is uniform (see, e.g., Thomas 2002 and Khan and Thomas 2008) with upper bound $B_k = 0.0115$. Finally, to specify monetary policy we set $\phi_\pi = 1.5$, $\phi_y = 0.5/4$ and $\phi_r = 0.7$.

2.5 Numerical Method

A detailed description of our numerical method is provided in the Appendix. The method is based on Reiter (2009), which can be understood as the heterogeneous agents analogue of the linearization method that is widely used in business cycle models and in the literature on monetary policy. It gives a solution that is fully

nonlinear in the individual optimization problem, but linearized in the aggregate variables, which include the cross-sectional distribution of capital and prices. In computing fluctuations, the method keeps track of a high-dimensional representation of the cross-sectional distribution. Because this distribution (the state-space of our model) is larger than what can be handled even by a linearization model, we apply the optimal state reduction technique of Reiter (2010).

3 Results

3.1 Steady State

Let us start by analyzing how the interaction of (S,s) pricing and investment decisions affects the stochastic steady state of our model. To this end it is useful to introduce one friction at a time. First, we assume that investment is lumpy but that prices are fully flexible. The implied ergodic set is illustrated in Fig. 1. The size of each point in Fig. 1, 2 and 3 indicates the associated probability mass and we only consider points whose probability mass is not smaller than 10^{-5} times the maximum point mass in the ergodic set.

[Figure 1 about here.]

Fig. 1 shows that firms with a relatively large capital stock choose a relatively small price. This is intuitive. With flexible prices a firm implements the desired markup over its marginal cost period by period and a firm's marginal cost is inversely related to the size of its capital stock. Moreover, all investors choose the same capital stock (regardless of the relative price that is in place by the time when the investment decision is made). This is another intuitive finding since the restriction on capital adjustment is the only source of heterogeneity in this simplified version

of our model. Next, we turn to the baseline calibration. The Fig. 2 illustrates the behavior of price-setters in the ergodic set.

[Figure 2 about here.]

Once again a clear pattern emerges. The larger a firm's capital stock the smaller the chosen relative price. There are, however, some important differences with respect to the flexible price version of our model. For large enough capital stocks the chosen prices are larger than their counterparts under flexible prices whereas the opposite is true at lower capital levels. The reason is as follows. To the extent that prices are sticky they are set in a forward-looking manner. Specifically, a firm takes rationally into account that its relative price will decrease over time (due to steady state inflation) as long as it is not reset. In addition the firm's capital stock is expected to depreciate over the lifetime of the chosen price if no investment is expected to occur. Those considerations make price-setters with relatively large capital stocks choose prices that are larger than the ones that firms with the same capital stocks would choose in the presence of flexible prices. If a price-setter's capital stock is, however, smaller then it becomes more likely that an investment will take place before the price is reset. That is taken into account when price-setters form expectations regarding their marginal costs over the lifetimes of the chosen prices. This explains why newly set prices that are chosen by firms with relatively small capital stocks are smaller than the corresponding flexible prices.

[Figure 3 about here.]

Fig. 3 shows the newly chosen capital stocks. For large enough relative prices the chosen capital stock is a decreasing function of a firm's relative price. However, for lower relative prices this relationship becomes backward-bending. The reason is as follows. The smaller an investor's price the likelier it is that this firm will increase

its price over the expected lifetime of the chosen capital stock. This in turn limits the size of the capital adjustment that the firm undertakes. With those preparations we now turn to the ergodic set implied by our baseline calibration. This is shown in Fig. 4.

[Figure 4 about here.]

There are many different groups of firms as a consequence of the interaction of pricing and investment decisions. We have already discussed the subsets of the ergodic set that correspond to newly set prices and newly chosen capital stocks. If a firm does not adjust neither its price nor its capital stock for the next period then that firm moves down and to the left in the figure due to the effects of steady state inflation and depreciation. This is reflected in the lines that are parallel to the ones which correspond to the optimally chosen prices and capital stocks. Finally, the figure also documents that price-setting occurs more frequently than investment under our baseline calibration. In fact, the lowest capital levels that are visited in the ergodic set are reached because firms find it optimal to let their capital depreciate over extended periods if they increase their prices from time to time in the meanwhile.

Having analyzed some important steady state properties of our model we now turn to the central question of the present paper. Does New Keynesian theory imply a quantitatively relevant monetary transmission mechanism in the presence of lumpiness in plant-level investment?

3.2 The Monetary Transmission Mechanism

We wish to isolate the role of a realistic degree of lumpiness in plant-level investment for the monetary transmission mechanism. It is therefore natural to start by considering a model which is closely related to standard treatments of that mecha-

nism.⁸ More concretely, we assume Calvo (1983) pricing combined with a restriction on firm-level investment which takes the form of a convex capital adjustment cost. This model therefore features endogenous capital accumulation at the firm-level, but no lumpiness in investment. Specifically, the restriction on capital adjustment (which now replaces equation (8)) takes the following form

$$C_{k,t}(K_t(i), K_{t+1}(i)) = \frac{\kappa}{2} (K_{t+1}(i) - K_t(i))^2. \quad (14)$$

Parameter κ takes the value 20, which is a conventional choice. Under the Calvo (1983) assumption each firm faces a constant and exogenous probability of getting to reoptimize its price in any given period. In order to be consistent with our baseline calibration this probability is set to 0.25. Whenever Calvo pricing is used in our analysis we also stick to the convention of combining it with the assumption of zero inflation in the steady state.⁹ The remaining parameters are held constant at their baseline values.

[Figure 5 about here.]

Fig. 5 illustrates the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate. The rate of inflation as well as the real interest rate are also annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value. The findings are similar to the corresponding outcomes in Galí (2008, p.53). He observes that the dynamic consequences of monetary policy shocks, as implied by a Calvo pricing model without endogenous capital accumulation, are (at least qualitatively) consistent with the empirical evidence that has been obtained using structural vector autoregressive methods. Not surprisingly, given the analysis in Woodford (2005), a similar obser-

⁸See, e.g., Woodford (2005).

⁹See, e.g., Woodford (2005) and Galí (2008).

vation can be made for our version of the Calvo model featuring a convex capital adjustment cost at the firm level. In fact, this model predicts that monetary policy shocks have strong and persistent consequences for real variables. For instance, the estimates reported by Christiano et al. (2005) indicate that the maximum output response to an identified monetary policy shock is about 0.5 percent (with 95 percent confidence interval around this point estimate of about ± 0.2).¹⁰ After that, output is estimated to take about one and a half years to revert to its original level which is in line with the model's prediction. Christiano et al. (2005) also estimate a maximum investment response of about one percent (with 95 percent confidence interval around this point estimate of about ± 0.5). The estimated maximum consumption response is roughly 0.2 percent (with 95 percent confidence interval around this point estimate of about ± 0.1). By and large, the model under consideration model is consistent with that evidence. Moreover, this model is able to capture the observed inertial behavior of inflation, and the maximum inflation response lies in the empirically plausible range. In fact, Christiano et al. (2005) estimate a maximum inflation response of roughly 0.2 percent (with 95 percent confidence interval around this point estimate of about ± 0.15).¹¹ Consistent with the somewhat large impact responses of the real variables the impact inflation response is to the low part of the above mentioned confidence interval. Finally, the nominal interest rate takes about two quarters to return half-way to its preshock level which is another feature of this model that is in line with the estimates reported in Christiano et al. (2005).

How does the monetary transmission mechanism change when the New Keynesian model is augmented by a standard model of lumpy investment? We will analyze

¹⁰The maximum response is estimated to occur about six quarters after the shock. This is one reason why additional real and nominal frictions are typically added to New Keynesian models in order to increase their empirical realism. See, e.g., Christiano et al. (2005).

¹¹The estimated maximum inflation response occurs about two years after the shock.

this question under alternative assumptions regarding the price-setting of firms. It is natural to make one change at a time with respect to the model that we have just considered, i.e., in the first step we keep the assumption of Calvo (1983) pricing and combine it with our preferred calibration of lumpy investment. Once again, we consider dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate. Fig. 6 illustrates the result.

[Figure 6 about here.]

In the presence of lumpy investment and Calvo (1983) pricing monetary policy shocks imply counterfactual effects on real variables. Specifically, that model predicts an impact response of output to the monetary disturbance of about 3 percent, i.e., about 6 times as much as the corresponding point estimate in Christiano et al. (2005). Moreover, the investment impact response to the shock is about 12 times as large as the corresponding point estimate and also the relative size of the investment response compared to the consumption response is not in line with the data. While the impact inflation response predicted by this version of our model is in the empirically plausible range, the pronounced deflation in the aftermath of the shock is another unrealistic prediction of this version of the model.

We now ask if an empirically relevant monetary transmission mechanism can be restored if we allow for state-dependent pricing in the context of our lumpy investment model. Fig. 7 shows that this is not the case. The theoretical results are still out of line with the corresponding empirical estimates if our baseline calibration with a state-dependent pricing decision is used. In that case the impact response of output to a monetary policy shock is somewhat smaller than the corresponding outcome in the lumpy investment model with Calvo pricing, but it is still substantially larger than the estimate in Christiano et al. (2005). Moreover there is now an almost complete lack of persistence in the real consequences of the shock

and the relative split between investment and consumption in the aftermath of the shock is still out of line with the empirical evidence. In a way that is consistent with the smaller impact responses of the real variables to the monetary disturbance we also find that the impact inflation response is now about 6 times larger than the estimated maximum response in the data. Finally, we analyze the monetary transmission mechanism under a uniform price adjustment cost density.¹² The results are also shown in Fig. 7. The impact response of output is reduced with respect to our baseline specification. It now takes a value of about 1 percent. At the same time, however, there is still no persistence in the dynamic consequences of monetary disturbances, the relative size of the investment response compared to the consumption response remains counterfactual, and the inflation response to the shock is further increased with respect to our baseline calibration. Taken together, those results show that lumpy investment, if modeled as it is common in the investment literature, fails to give rise to a realistic monetary transmission mechanism in the context of otherwise standard versions of the New Keynesian model.

[Figure 7 about here.]

Let us explain the economic mechanism behind our results. If investment decisions are conducted in an (S,s) fashion then firms choose the timing of those decisions optimally. As in the RBC models analyzed by House (2008), firms therefore tend to front-load investment decisions by the time when a shock hits the economy. In the context of our model, firms take rationally into account that the decrease in the real interest rate that is triggered by the monetary policy shock makes it particularly profitable for them to invest by the time when the shock hits the economy. They therefore undertake some of the investment activity that they would have otherwise

¹²The upper bound of the support is chosen in such a way that the average frequency of price adjustment is 0.25, as in our baseline model.

done later. This is important for two reasons. First, the impact investment response to the shock becomes very large. Second, the distribution of firms in the economy is altered in such a way that investment in subsequent periods becomes less likely. This explains both the enormous size of the impact response of investment to a monetary disturbance (which is driving the large output response) and the almost complete lack of persistence in the dynamic consequences of that shock. But what is the reason behind the additional flexibility of inflation that is implied by (S,s) pricing compared to the Calvo model? The answer to that question is an extensive margin effect à la Caballero and Engle (2007), i.e., the fact that some firms increase their prices in response to an expansionary monetary policy shock precisely because the monetary disturbance makes them reach the threshold for upward adjustment. In the Calvo model this effect is absent. Those firms which face an infinitely large adjustment cost will not respond to the monetary disturbance and the remaining firms would also adjust if there was no shock because this is costless for them. If the cost distribution is, however, changed in such a way that the probability mass is concentrated around intermediate values then the fraction of firms facing costs that are too extreme to make the monetary disturbance trigger a price increase becomes smaller. In other words, the extensive margin effect becomes stronger. This is the reason why inflation reacts more to a monetary policy shock if the price cost distribution is changed from Calvo to baseline to uniform, and the real consequences of monetary disturbances become consequently smaller after each change in assumption.

The magnitude of the problem posed by the presence of lumpy investment for the New Keynesian monetary transmission mechanism is remarkable. It might therefore seem surprising that Johnston (2009) finds that this feature appears to imply only relatively modest changes with respect to standard treatments of that mechanism. This discrepancy in results has, however, a very simple reason, as discussed next.

3.3 A Note on Johnston (2009)

As already mentioned, Johnston (2009) has also investigated the effect of monetary shocks in a framework that integrates (S,s) pricing and investment decisions in general equilibrium and his conclusions appear to contradict ours. In fact, his model implies that the presence of lumpy investment lowers somewhat the persistence in the real consequences of monetary disturbances (compared to a model with a convex capital adjustment cost), but has otherwise no dramatic consequences. This is in stark contrast with our main result according to which lumpy investment destroys the monetary transmission mechanism as we know it from the textbooks. Where does this discrepancy in results come from? There are a number of differences between the two models. Johnston (2009) assumes a stationary process for the growth rate of real balances, whereas we consider an interest rate rule for the conduct of monetary policy. Moreover he assumes that if a firm wants to adjust its capital, it must also adjust its price.¹³ The last assumption implies a reduction in the extensive margin effect discussed above (because some firms reoptimize their prices regardless of the realization of the monetary policy shock). Consequently, the price level becomes relatively smooth. Finally, Johnston assumes the quantity equation according to which real money balances, $\frac{M_t}{P_t}$, are equal to aggregate real output, Y_t , or, equivalently, $M_t = Y_t P_t$. If money growth is exogenous and prices are sticky then the last equation implies that aggregate real output must evolve in a smooth fashion. In order to show that this simple observation explains the difference between his findings and our main result we now modify the baseline version of our model in the following way. We replace the interest rate rule for the conduct of monetary policy by a money growth rule (with the autoregressive parameter set to the conventional

¹³ Johnston (2009) also assumes that the capital good is produced by the household with a one period delay but can be installed and used by firms immediately.

value of 0.5) and combine it with the quantity equation à la Johnston. This change in assumption has important consequences for the implied monetary transmission mechanism, as Fig. 8 makes clear.

[Figure 8 about here.]

We consider a 1 percentage point increase in the growth rate of money balances. If the restriction on price adjustment takes the form of the Calvo (1983) mechanism aggregate real output (and inflation) display the typical inertial behavior in the aftermath of that policy shock. Those results are consistent with the central finding in Johnston (2009). It is important to realize, however, that the smoothing mechanism which is implied by the quantity equation combined with the assumption of exogenous money growth is much less important in the presence of a state-dependent pricing decision. The reason is the additional flexibility of the price level. This is also shown in Fig. 8. We therefore conclude that the difference between our results and the ones in Johnston (2009) is due to a smoothing mechanism which relies on the quantity theory combined with assumptions which make sure that two out of the three variables entering that equation evolve in a smooth fashion in the aftermath of the considered monetary policy shock.

3.4 Robustness Analysis

Let us now go back to our baseline model. Unless stated otherwise the variations considered below are consistent with the evidence on price-setting and on investment decision making that we have discussed in the calibration part of our text. We start by analyzing a version of our model where the stochastic fixed capital adjustment cost is combined with a convex cost of the form specified in equation (14).¹⁴ This

¹⁴There has been some recent interest in the analysis of general adjustment cost functions. For instance, Cooper and Haltiwanger (2006) allow for both convex and non-convex elements in capital

brings out an interesting result. As long as our calibration is consistent with the micro evidence on lumpy investment the presence of a convex capital adjustment cost does not lead to a realistic monetary transmission mechanism.¹⁵ This is shown in Fig. 9.

[Figure 9 about here.]

Once again, we consider the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate. We consider two alternative values ($\kappa = 1$ and $\kappa = 5$) for the convex component of the capital adjustment cost. In each case the presence of the convex cost results in a reduction of the impact responses of the real variables to the monetary policy shock (compared with the baseline case that is also shown in Fig. 9). There is, however, no persistence in the dynamic consequences of that shock. The economic reason is simple. As long as our model is consistent with the observed lumpiness in investment the front-loading motive that we have discussed above remains quantitatively important and the intuition that we had developed for our main result still goes through.

We also assess the robustness of our main result along other dimensions. Compared with our baseline calibration we now change one parameter value at a time.¹⁶ We start by analyzing the consequences of setting the maintenance parameter, χ , to zero. Not surprisingly, this calibration implies too many investment spikes. However, as Fig. 10 makes clear, there is no important change in the dynamics implied

adjustment costs. Their estimates imply that a model, which mixes both convex and non-convex adjustment costs, fits the data best.

¹⁵We have also considered a hybrid specification of the investment process, where in each period 75% of all firms (randomly chosen) adjust their capital à la Calvo as in Sveen and Weinke (2007), and only 25% have state-dependent investment. The 25% chance of state-dependent behavior makes investment so flexible that we get results similar to our baseline case.

¹⁶We have also analyzed the consequences for the monetary transmission mechanism of changing the timing convention in the firms' optimization. If investment takes place before price-setting the resulting monetary transmission mechanism remains counterfactual. Those findings are available upon request.

by our model. The observation that the presence of maintenance helps explain the micro evidence on lumpy investment without affecting much the aggregate dynamic properties of the model is also consistent with some of the findings in Gourio and Kashyap (2007).

[Figure 10 about here.]

Next, we vary the convexity in the disutility of supplying hours, ϕ . The results are shown in Fig. 11.

[Figure 11 about here.]

Also in this case we find some small changes in the implied impulse responses compared with the baseline case. Our main result according to which the presence of lumpy investment makes our model inconsistent with a realistic monetary transmission mechanism remains, however, intact. The economic reason is once again the front-loading motive in investment decision making.

Finally, we consider alternative interest rate rules for the conduct of monetary policy. Specifically, we compare our baseline with two alternative rules one of which prescribes that the central bank does not adjust the nominal interest rate in response to changes in real economic activity, i.e., parameter ϕ_y is set to zero in this rule. The other interest rate does not feature any interest rate smoothing, i.e., parameter ϕ_r is set to zero in this rule. In each case the remaining coefficients in the interest rate rule are held constant at their baseline values. The results are shown in Fig. 12.

[Figure 12 about here.]

To the extent that prices are sticky the form of monetary policy plays an important role in shaping the dynamic responses of macroeconomic variables of interest to a monetary policy shock. This general observation also applies in our model. For

empirically plausible specifications of monetary policy we find, however, no evidence in favor of a realistic monetary transmission mechanism.

4 Conclusion

Models of monetary policy usually assume convex costs of capital adjustment (see, e.g., Christiano et al. 2005, Woodford 2005). This helps explain the macroeconomic evidence on the monetary transmission mechanism, but contradicts the observed lumpy nature of investment at the plant level. Is this just an innocuous simplification? Our answer is no. In an otherwise standard New Keynesian framework, we introduce (S,s) investment decisions as they are routinely modeled in current investment theory. Our main result shows that a quantitatively relevant monetary transmission mechanism cannot be entertained in the context of this model. In fact, with non-convex capital adjustment costs, neither different forms of state-dependent pricing nor time-dependent price-setting à la Calvo can generate dynamic consequences of monetary policy shocks that are consistent with their counterpart in the data.

Our results therefore show that investment behavior is crucial for the monetary transmission mechanism, but that we are still a step away from a monetary model that is compatible both with the macro- and the micro-evidence on investment behavior. This does not necessarily mean that there is anything wrong with the way how monetary policy or the price-setting by firms is modeled. It may well be that current investment theory is omitting important frictions (perhaps at a higher level of aggregation than the plant level) that would make investment less responsive to changes in the real interest rate. Moreover, as we were mentioning in the first sentence of the introduction, the presence of lumpiness is observed for

many microeconomic decisions. Given the empirical evidence in Bloom (2009) the addition of labor adjustment costs might be a particularly promising extension of the framework presented in the present paper. These issues are high on our research agenda.

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Appendix: Numerical Method

Each firm, indexed by i , has two individual state variables, capital $K(i)$ and last period's price $P(i)$. For the numerical solution, we use a discrete rectangular grid in the log of $K(i)$ and in the log of the firm's relative price $p(i) \equiv P(i)/P$. The grid is centered around the steady state values of those variables. The distance between grid points in $\log(K)$ -direction equals $m \log(1 - \delta)$ for some integer m , such that a firm which does not adjust its capital stock just moves m steps down the grid. If a firm that starts at a point of the grid and does not adjust its price, then it moves down the grid by the equivalent of the inflation rate. However, since the inflation rate is not constant, the firm cannot in general stay on the grid, so we choose the step size of the $\log(p)$ -grid independently of the inflation rate.

Both decisions of the firm, optimal K and optimal p , are continuous choices. To make this possible, the value of the firm's problem between grid point is approximated by piecewise-quadratic functions.

Given optimal firm choices, the dynamics of the cross-sectional distribution of capital and prices is computed by a discrete approximation to the continuous law of motion. Concretely, the distribution is represented as the distribution of firms over the $(\log(K), \log(p))$ grid described above. If a firm chooses an optimal $(\log(K^*), \log(p^*))$ that is not on the grid, this move is approximated as a stochastic transition to the grid points that are closest to $(\log(K^*), \log(p^*))$, such that the expected value of K and p is preserved.

Solving for the steady state is a two-dimensional fixed point problem in aggregate demand Y and wage rate W :

1. Given a guess of Y and W , we solve the firm's problem by value function iteration, using piece-wise quadratic interpolation of the value function between

grid points.

2. Given optimal firm choice, we compute the ergodic distribution of the cross-sectional distribution of prices and capital. We do this not by simulation, but by finding the eigenvector corresponding to the unit eigenvalue of the transition matrix of the distribution (see, Reiter 2009). Given optimal firm policy and the ergodic distribution of K and p , we can check whether they are consistent with the guesses of Y and W .
3. We solve for equilibrium Y and W by a quasi-Newton method.

Having computed the steady state, we compute the dynamics by linearizing the model around the steady state. For this, we write the whole model as a very large system of nonlinear equations. The variables of this equation system are the fraction of firms at each point of the $\log(K), \log(p)$ -grid, the value function of the firm at each point of this grid, furthermore the aggregate shocks and some more aggregate variables (such as output, labor input, wages etc.)

This gives a system of around 68400 equations in the same number of variables. This system is linearized around the steady state. To reduce the number of variables, we consider only points of the $\log(K); \log(p)$ -grid, that have a positive mass of firms in the ergodic distribution. This reduces the set of variables to 11283 in the baseline case. Since the resulting system is still too big to be solved on a normal PC, we reduce the number of variables still further by the methods of optimal state reduction developed in Reiter (2010). In the baseline case, this leaves us with 185 state and 137 jump variables. For more details of the solution procedure, see Appendix A of Reiter (2010). The model there is somewhat simpler than the present model, but the solution procedure is the same.

To check the accuracy of the solution, we vary the number of grid points in

K and p . It turns out that the results are not sensitive to reasonable variations in the size of the grid. Conditional on a grid size, the large linearized dynamic stochastic model can be solved with a precision that is in the range of square root machine precision (10^{-8}). This is explained in Reiter (2010). Of course the solution is subject to an approximation error insofar as it results from a linearization around the steady state. This is a feature that our solution shares with most models in the New Keynesian literature.

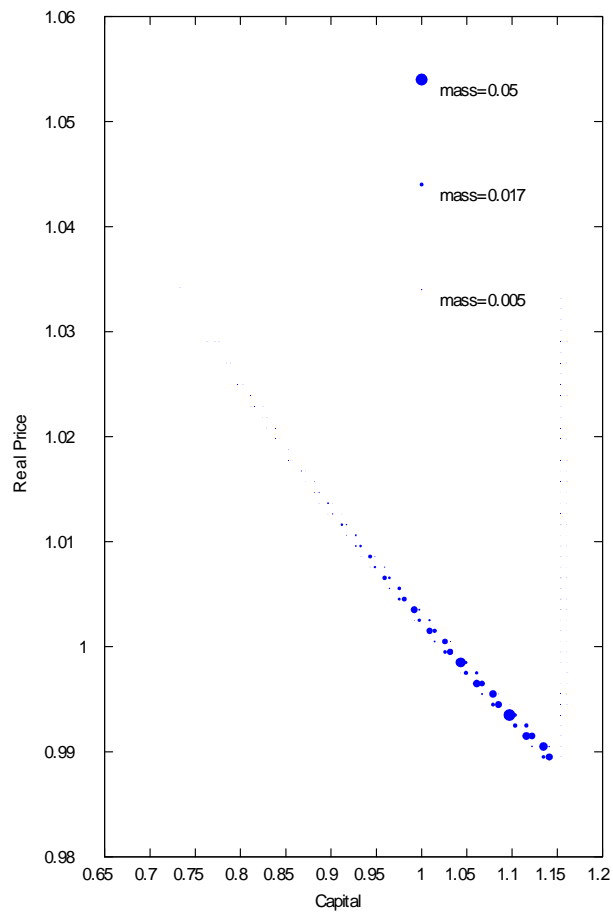


Figure 1: Ergodic Set for Flexible Prices.

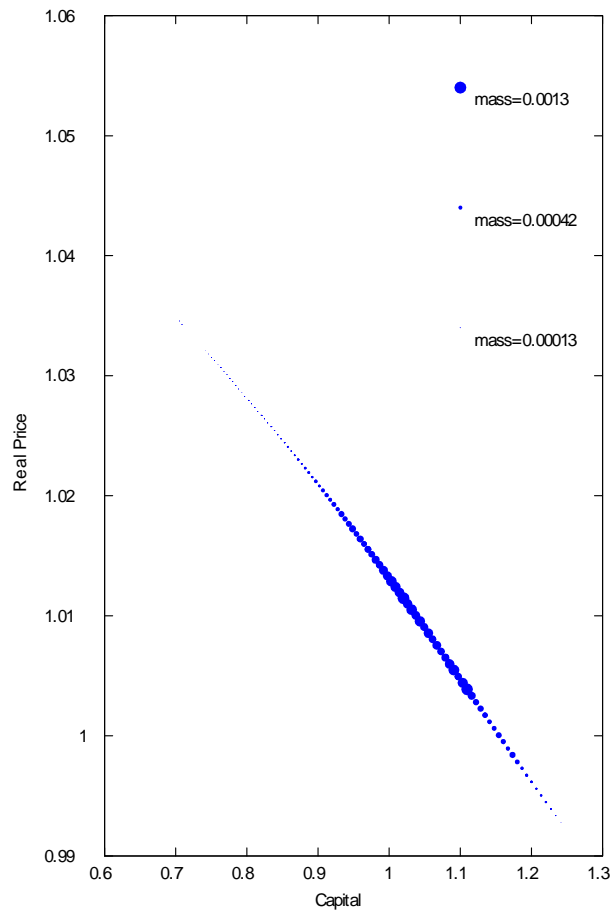


Figure 2: Newly Chosen Prices (Baseline)

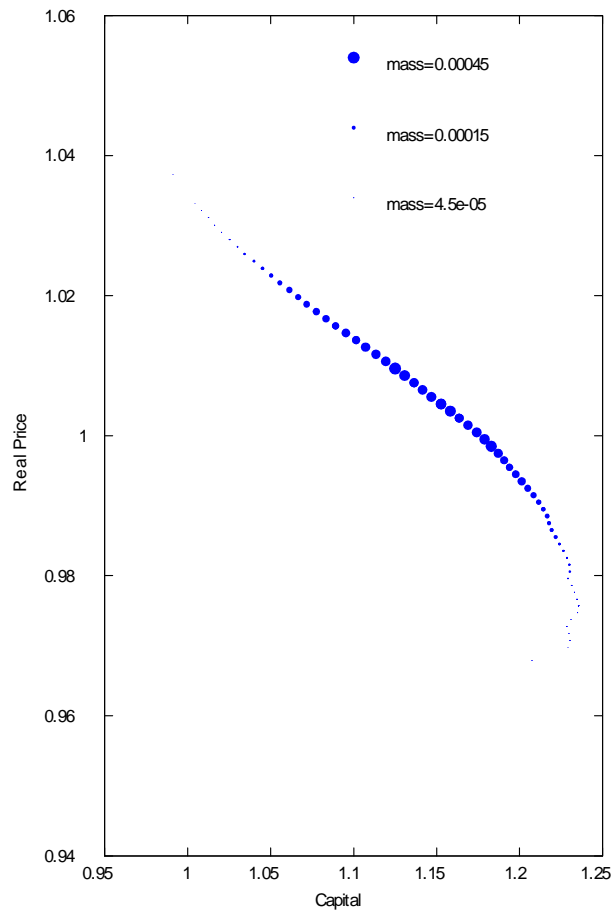


Figure 3: Newly Chosen Capital Stocks (Baseline)

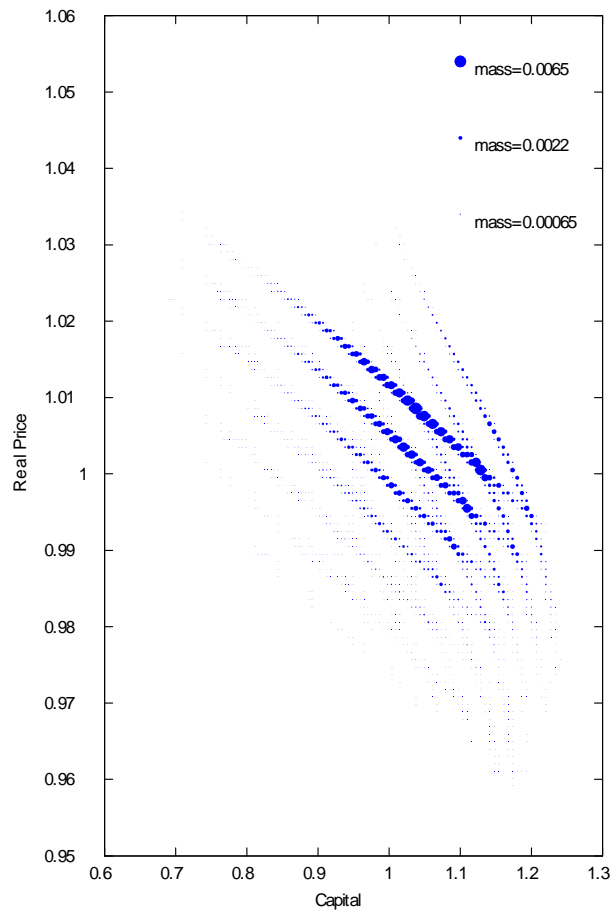


Figure 4: Ergodic Set (Baseline)

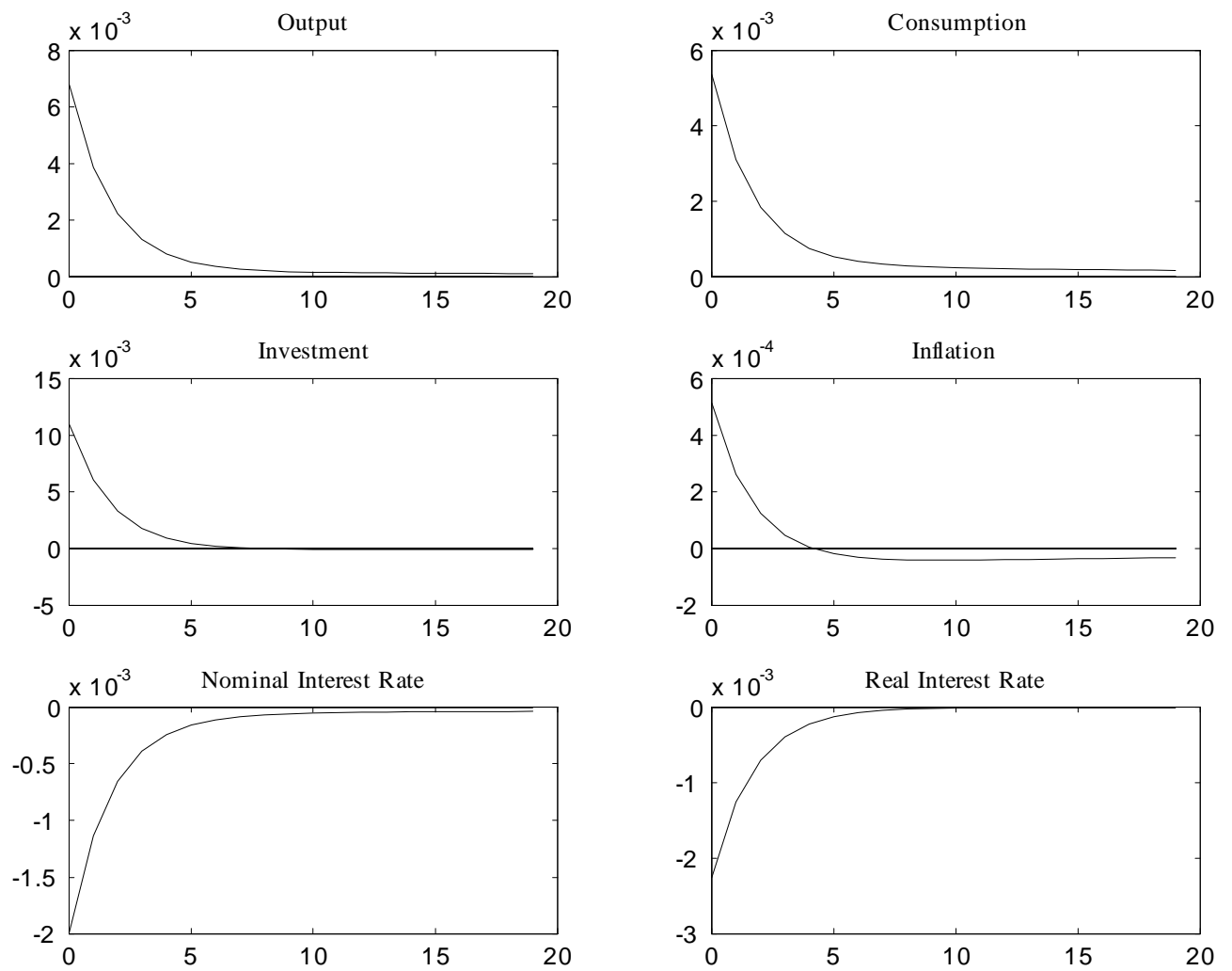


Figure 5: Monetary Policy Shocks with Convex Capital Adjustment Cost and Calvo Pricing.

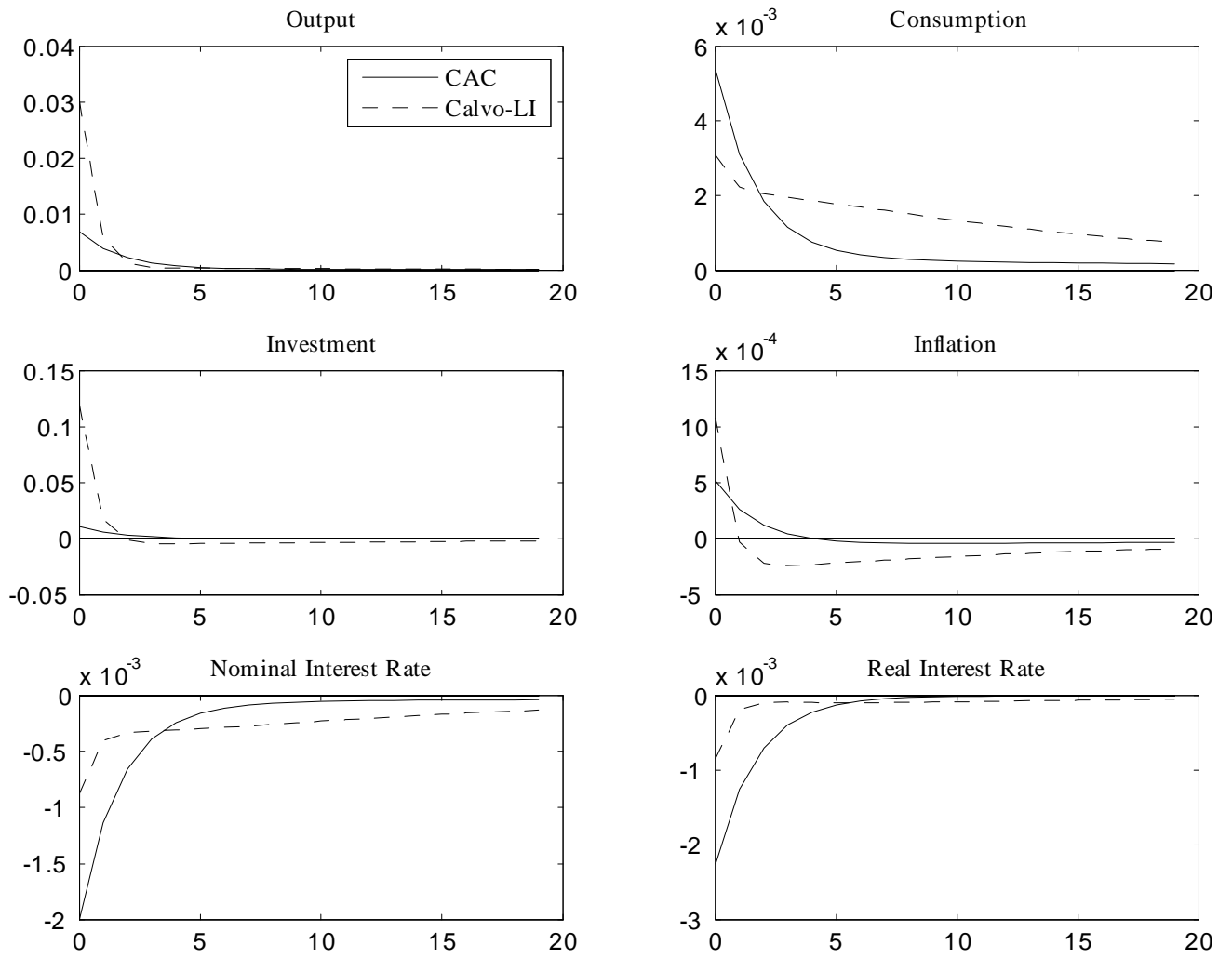


Figure 6: Monetary Policy Shocks with Endogenous Capital and Calvo Pricing

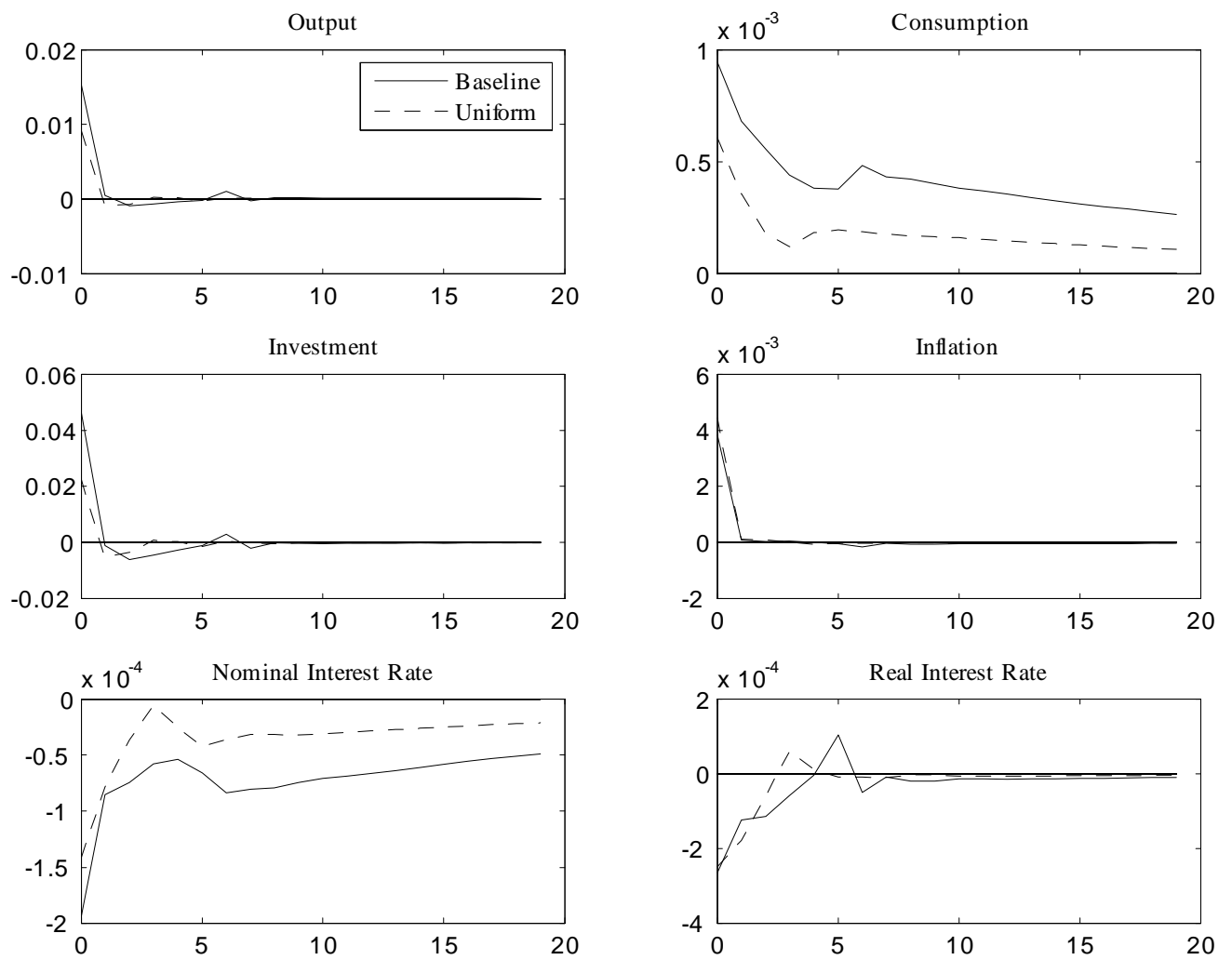


Figure 7: Monetary Policy Shocks with Lumpy Investment and State-Dependent Pricing.

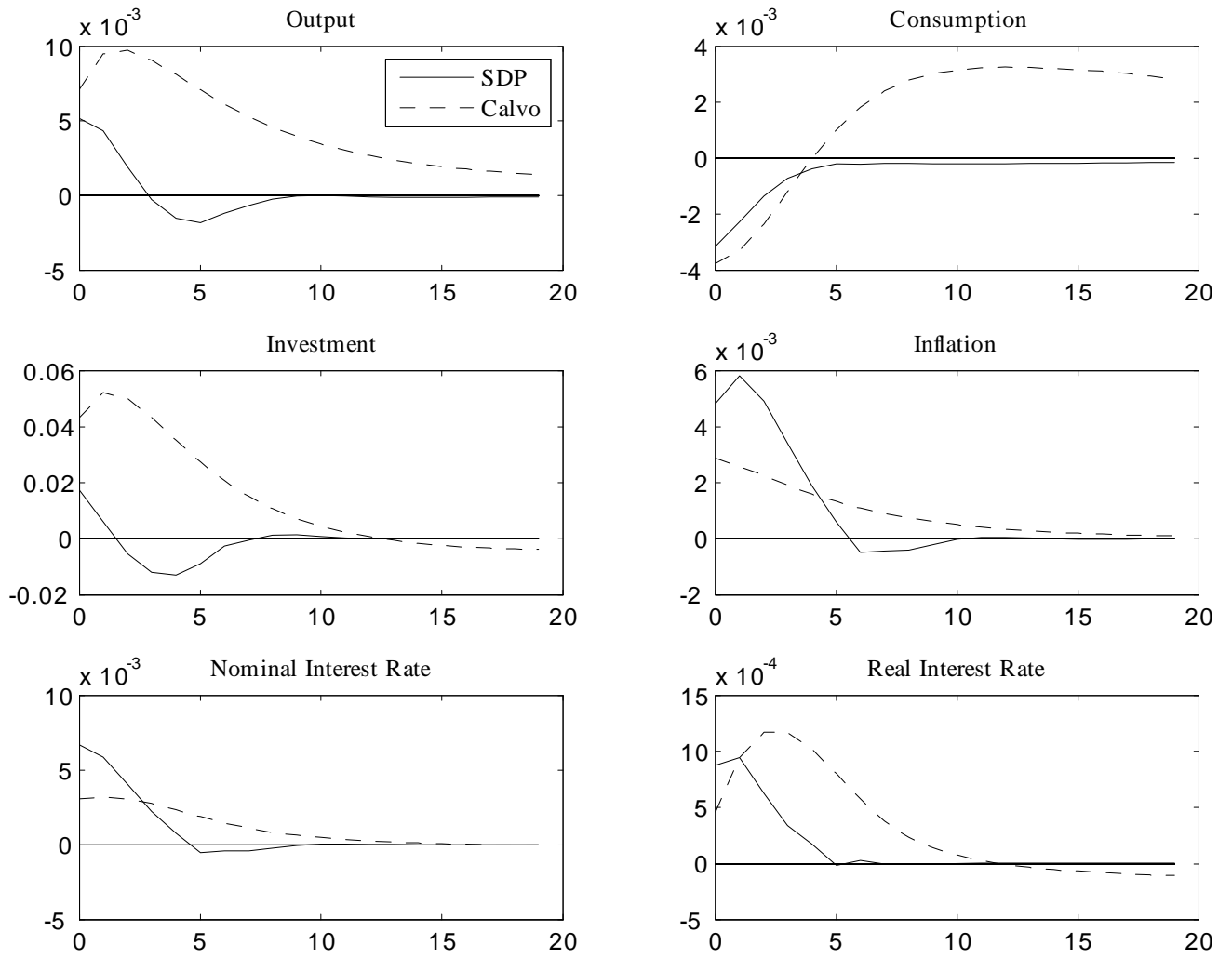


Figure 8: Shocks to Money Growth with Lumpy Investment and Sticky Prices.

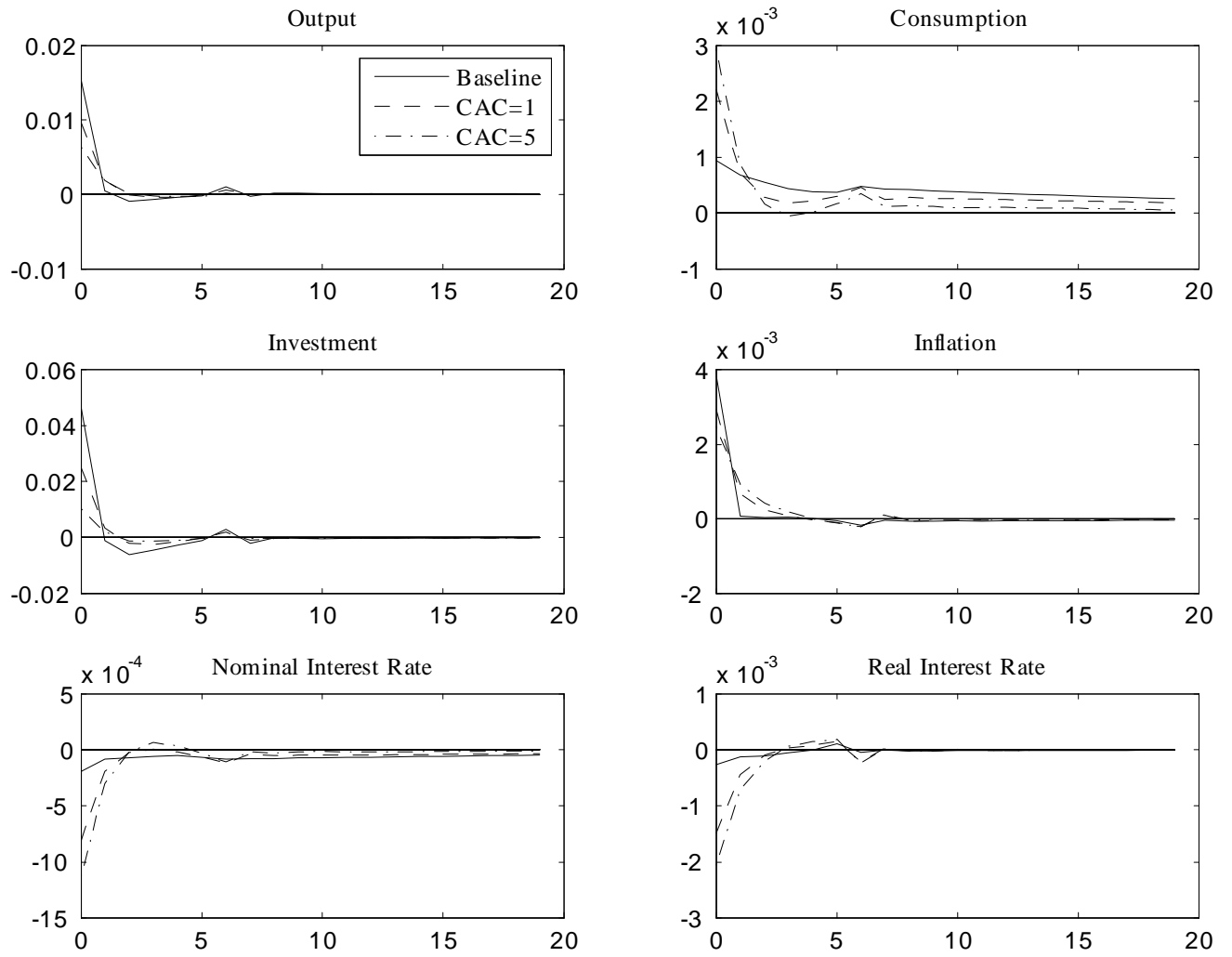


Figure 9: Convex and Non-Convex Capital Adjustment Costs (Robustness).

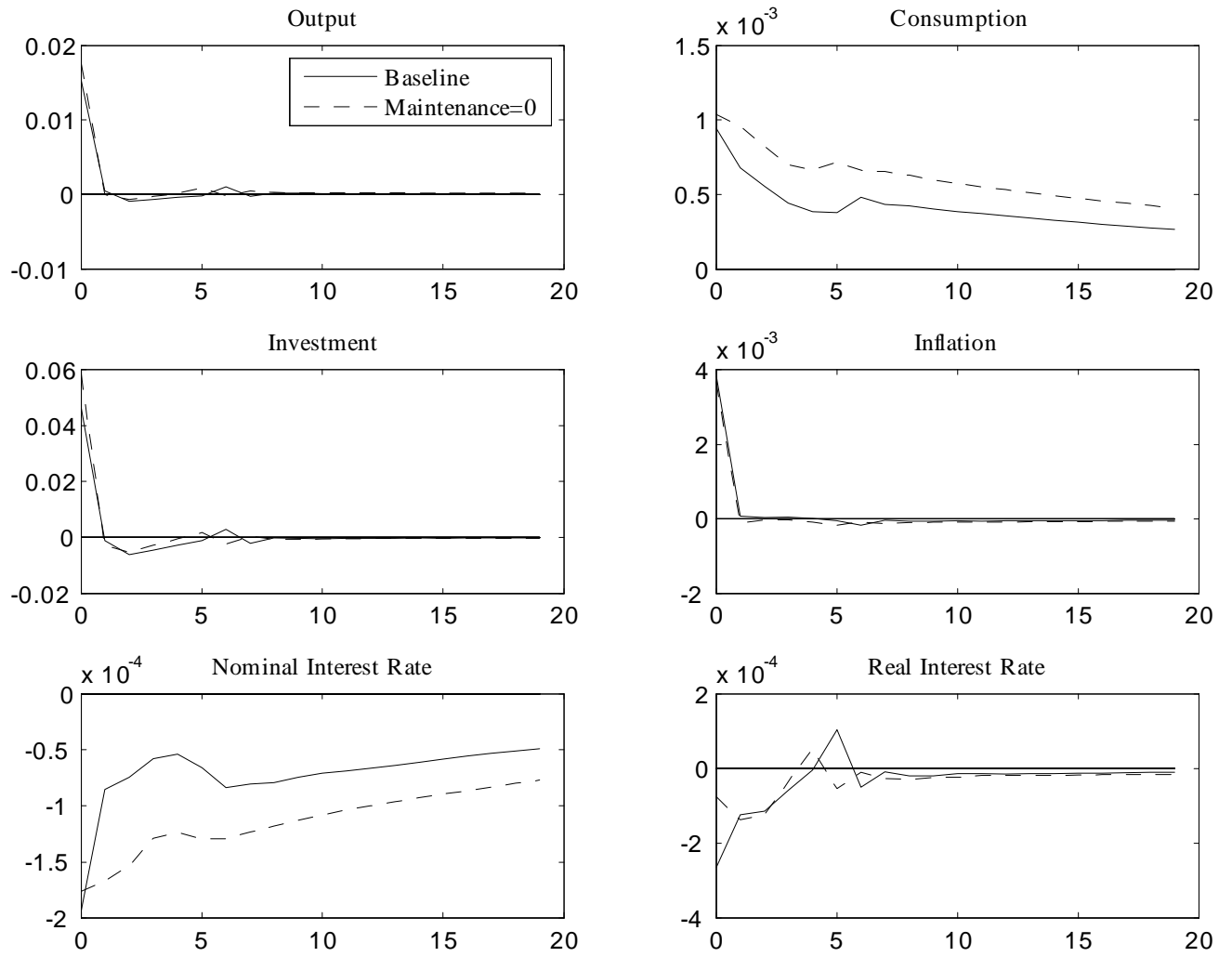


Figure 10: The Role of Maintenance (Robustness).

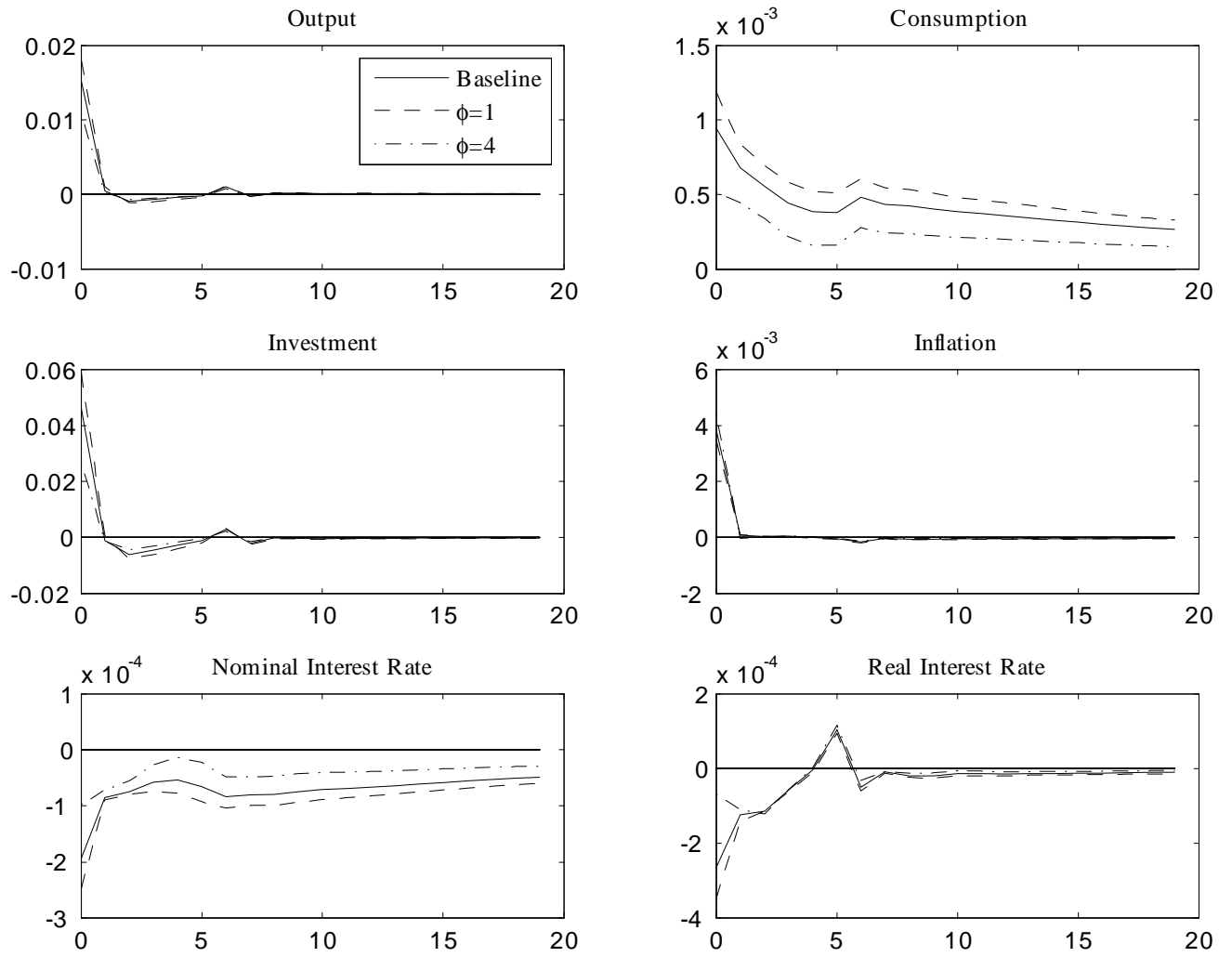


Figure 11: The Role of Disutility of Work (Robustness).

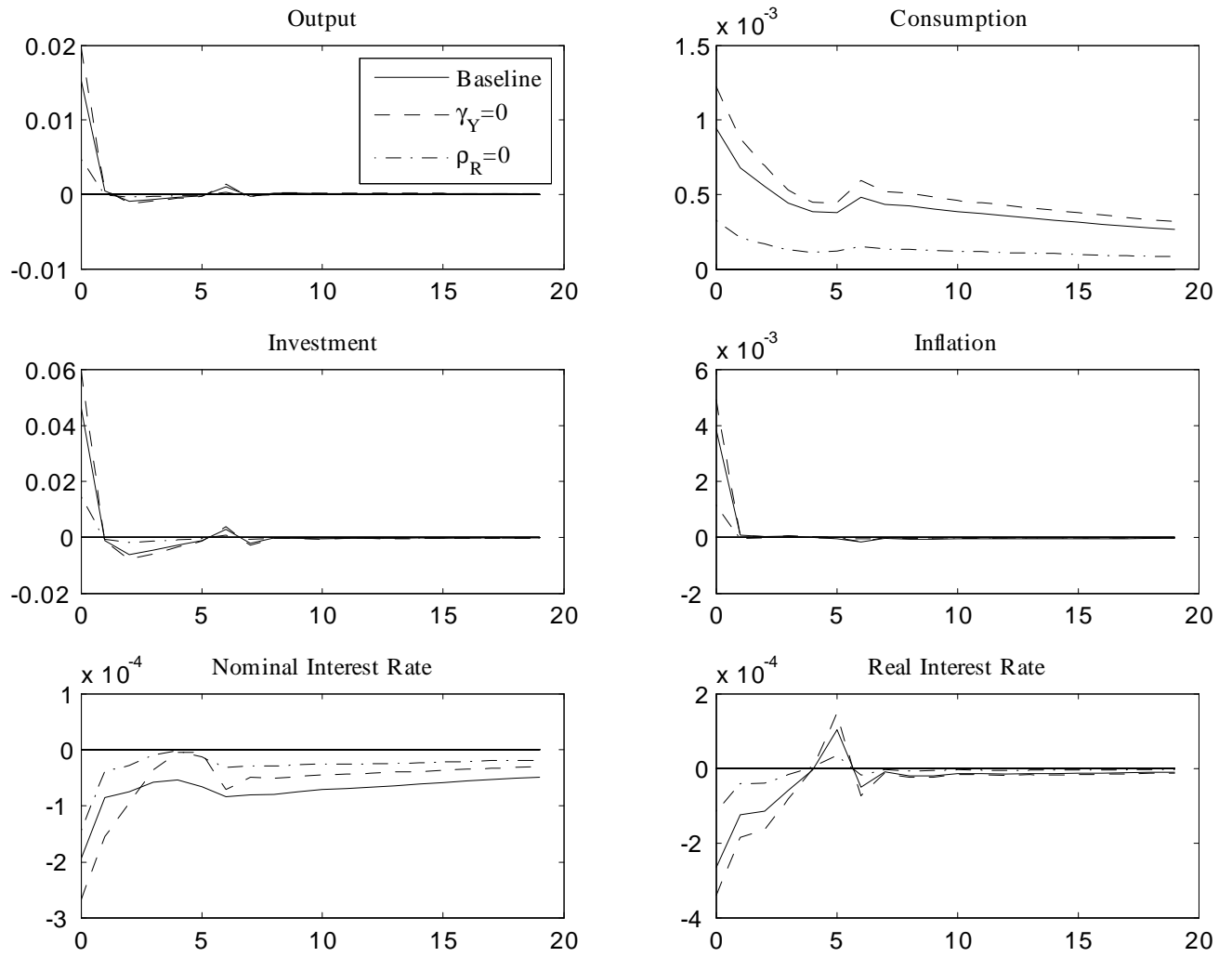


Figure 12: The Role of Monetary Policy (Robustness).