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INFLATION INERTIA — THE ROLE OF MULTIPLE, INTERACTING PRICING RIGIDITIES

Michael Kumhof

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Michael Kumhof
Stanford University
and
Hong Kong Institute for Monetary Research

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Abstract

Monetary models with nominal rigidities are known to have difficulties in matching some important features of the empirical impulse responses of monetary policy shocks, especially inertia of the inflation rate and the hump-shaped responses of consumption, investment and output. To remedy this, the literature has mostly employed a combination of backward-looking price setting and of not always uncontroversial real rigidities.

This paper addresses the problem without a need to depart from rational forward-looking price setting in a fully specified microfounded model. While price and wage setters are subject to nominal rigidities, they can choose a more generalprice path than in conventional models. Combined with econometrically identified highly persistent monetary policy shocks, this gives rise to far more persistent inflation and real interest rates. Second, a small number of simple and intuitively appealing real rigidities goes a long way in matching empirical impulse responses for real variables. These are habit persistence in consumption, time to build investment with an initial quadratic capital stock adjustment cost, and a long chain of intermediate input supply relationships, with nominal rigidities cascading from upstream to downstream.

The paper is at this stage mostly a theoretical and qualitative exercise. The detailed matching of empirical and model impulse responses is the subject of ongoing work.

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1. Introduction

Monetary models with nominal rigidities can successfully account for many effects of monetary policy. This is documented among others in Taylor (1998) and Clarida, Galí and Gertler (1999). But they are nevertheless known to have difficulties in matching some important features of the empirical impulse responses for monetary policy shocks. Mankiw (2001) notes that they do not generate the empirically observed inflation inertia (delayed inflation response), and Fuhrer and Moore (1995) show that they also do not generate the observed inflation persistence (prolonged inflation response). Ball (1994a,b) shows that in these models disinflationary policies have minimal real costs, which is inconsistent with a large body of empirical evidence showing a U shaped output response (Gordon 1982, 1997). Finally, Christiano, Eichenbaum and Evans (2001) show that these models also have trouble matching the empirical impulse responses of a number of real variables other than output. To remedy these shortcomings, Christiano, Eichenbaum and Evans (2001) employ a combination of backward-looking price setting (indexation) and of at least partly controversial real rigidities. A different route is taken by Mankiw and Reis (2002) and Cespedes, Kumhof and Parrado (2003), who work with pricing specifications that are able to generate inflation inertia even under rational forward-looking price setting. But both papers are insufficiently detailed on the real side of the economy to be able to match detailed empirical impulse responses.[1] The present paper attempts to do so, building on the work of Cespedes, Kumhof and Parrado (2003).

It is well known that in order to impart inertia to inflation, a key feature of the data, a very important requirement is to dampen the speed of marginal cost adjustment to shocks; see for example Chari, Kehoe and McGrattan (2002) and Huang and Liu (2002). In models with conventional Calvo (1983) pricing assumptions this speed can be affected by two factors. One is a slow response of the input price components of marginal cost to output demand, i.e. nominal rigidities in input prices. The other is a slow response of output demand to monetary policy shocks. In our model several such factors are at work through a very detailed modeling of the real side of the economy, using real rigidities that are intuitively very appealing and (we hope) uncontroversial. However, inflation inertia can also come about through factors that are entirely independent of the cost and input side of production, specifically through the final output pricing policies from which producers are allowed to choose. We posit here the type of pricing policy pioneered by Calvo, Celasun and Kumhof (2001, 2002) and Cespedes, Kumhof and Parrado (2003), for price and wage setting.

Conventional models with nominal rigidities either restrict firms (or workers, for wage rigidity) to setting only a constant price level at each reoptimization (Woodford 2002), or to set an initial price level that is thereafter updated automatically at the steady state rate of inflation (Yun 1996). We suggest that, especially in the realistic case of a positive steady state inflation rate, it is more plausible to assume that firms employ pricing policies instead of setting only a price level. The purpose of such policies is to keep them as close as possible to their steadily increasing flexible price optimum between the times at which price changing opportunities arrive. To keep the model tractable, we specifically assume that once a firm gets the chance to change its pricing policy, it jointly and optimally chooses an initial price level and an unconditional rate at which it will update its price in the future, a 'firm specific inflation rate'. Pricing schemes that allow price setters even more degrees of freedom are certainly feasible, but only at the

[1] For example, neither paper features investment and capital accumulation.

expense of greatly increased complexity. That additional flexibility only makes a significant difference for the behavior of the model economy under fairly unusual shock experiments such as anticipated future disinflations. Our emphasis here is on monetary shocks identified from the data, and for such shocks our 2-part, ‘intercept slope’ pricing policy is sufficient. A major advantage of this specification is that it can be easily inserted into dynamic stochastic general equilibrium models, and standard recursive solution methods can be applied. Cespedes, Kumhof and Parrado (2003) contain a list of references that relate our modeling approach to other papers in this literature, most notably Mankiw and Reis (2002) and Burstein (2002).

We motivate our pricing specification by appealing to costs of reoptimization, such as costs of information gathering, decision making, negotiation and communication. The empirical evidence presented by Zbaracki, Ritson, Levy, Dutta and Bergen (2000) emphasizes the importance of reoptimization costs relative to menu costs (Akerlof and Yellen 1985), the most common motivation for nominal rigidities. This reoptimization costs rationale is also stressed by Christiano, Eichenbaum and Evans (2001).

When firms employ pricing policies of the kind we propose, an unexpected and highly persistent decline in the steady state inflation rate targeted by monetary policy entails a slow inflation response and output losses, even if the change in policy is perfectly credible. There are two main reasons for this. The first is the continuing effect of historic pricing decisions. The economy initially contains a large number of firms that have chosen their price updating rates under the previous policy, and the weighted average of such updating rates is an important component of aggregate inflation. Intuitively, because it is costly for firms to be continuously informed about monetary conditions, it takes time for their periodic inflationary updating to fully reflect the stance of monetary policy on inflation. The second reason for the slow inflation response is the behavior of new price setters. The spread between firms’ initially chosen price and the aggregate price level, or ‘front loading’, is the second component of aggregate inflation. Because firms have the option of updating their prices, front loading will respond very little to the policy change, contributing further to the sluggishness of the inflation response. And, of course, because pricing rigidities at upstream producers cascade downstream these effects are compounded.

Because the pricing scheme we suggest gives price setters two choice variables, the behavior of the model is very dependent on the interaction between the nature of the shock and the component of the pricing policy that price setters choose to adjust. In particular, if the shock is such that current price setters do not expect a very persistent change in the aggregate inflation rate, they will choose to mostly adjust the initial price level. In that case our model will behave very much like the Calvo Yun model, because it nests a conventional Calvo Yun model if all price setters’ updating rates are held constant. An example of such a shock is a transitory shock to the targeted inflation rate. But when the shock affects the expected aggregate inflation rate in a manner that is both sudden and persistent, price setters will optimally choose to significantly change their price updating rate. In that case inflation will be inertial and persistent. An example of such a shock is a sudden and highly persistent shock to the targeted inflation rate. The importance of suddenness is due to the fact that a shock that only slowly filters through to the central bank’s inflation target allows price setters’ updating of inflation rates to keep pace with the change in policy. This is important, because it means that a monetary policy rule modeled as interest rate smoothing, a very common approach, would not give rise to dramatically different performances between our model and a conventional sticky price model. Interest rate smoothing as an appropriate characterization of central bank behavior, and therefore as a modeling assumption, has however recently been subject to an important critique by Rudebusch (2002), who suggests that it is not consistent with evidence from the term structure of interest rates. On the other hand, an interest rate rule without smoothing is consistent with such evidence and with data for inflation and output so longasthe shocks to this ruleareallowed to be highly persistent.

In this paper we therefore estimate a monetary policy rule without interest rate smoothing by the generalized method of moments, and identify the residuals from that regression as monetary policy shocks. For most specifications of the rule, these shocks are indeed highly persistent. It is found that they are best represented as an AR(1) process with an autoregressive coefficient of 0.7-0.8. But estimating such a forward-looking policy rule without lags makes it more difficult to apply the commonly used Minimum Distance estimation method for our model, because this relies on matching the impulse responses of a vector autoregression (VAR) that includes the nominal interest rate. A VAR assumes that the behavior of the nominal interest rate can be characterized by a projection on past variables including its own lags, and this implicitly allows for interest rate smoothing. Incorporating our specification of the monetary policy rule into an estimation framework is an issue that we are currently researching. Pending a solution to this problem, the final part of this paper therefore relies at this stage on a parameterization of the model based almost entirely on parameter values suggested by the literature and on the estimated monetary policy rule and shock processes.

The remaining agenda of this paper concerns the qualitative matching of the empirical impulse responses of a number of real variables. The key issue here is that consumption, investment and output empirically exhibit hump shaped responses to monetary policy shocks. As discussed at the beginning, this slow response of output demand can also contribute to a slow response of inflation, thereby reinforcing the effect of pricing policies. Our model features habit persistence in consumption and a six period time-to-build assumption for investment combined with an initial quadratic capital stock adjustment cost.

The third mechanism generating persistent inflation and therefore persistent real interest rates is rigidity in input prices. This is where our assumption of multi-sectoral cascading pricing policies comes in. To explain this we use Figure 1, which shows the input-output linkages between the model economy's five production sectors and households. Households' labor wages are assumed to be rigid, and so are the output prices of all five productive sectors, namely an investment goods sector, a final consumption goods sector, and three intermediate inputs sectors. The marginal cost of a typical producer therefore consists of rigid labor wages, rigid intermediate input prices (for four out of five producers), and the return to capital. The cascading of nominal rigidities from upstream to downstream producers has a cumulative effect on the intermediate goods component of marginal cost for both final consumption goods and final investment goods.

Qualitatively, the model economy matches the data. We find that our type of pricing specification does indeed lead to more persistent inflation and real interest rates, and that in turn contributes to output persistence. Also, our combination of real rigidities goes a long way in generating hump-shaped impulse responses for real variables. A detailed quantitative analysis will be presented in future versions of this paper.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 estimates the monetary policy rule and presents impulse responses for a set of parameter values motivated from the literature. Section 4 concludes.

2. The Model

The economy consists of the following set of agents: (i) A continuum of infinitely-lived households indexed by $i \in [0,1]$, who take as given the prices of consumption and investment goods but who have market power in setting the wage for the variety of labor they supply. (ii) A competitive employment agency that combines the labor varieties supplied by individual households to produce homogenous labor. (iii) Five productive sectors: Final consumption goods and investment goods producers, and three intermediate input producers. In each of these sectors, there is a continuum of infinitely lived firms indexed by $j \in [0,1]$ who take the prices of their inputs as given but who are monopolistically competitive in the markets for their output. (iv) A government that sets monetary and fiscal policy.

2.1 Households

Household i maximizes lifetime utility, which depends on three arguments, per capita consumption C_t^i, leisure $(1 - L_t^i)$ and real money balances $m_t^i = (M_t^i / P_t^f)$, where M_t^i are nominal money balances and P_t^f is the consumption based price index for final consumption goods. Households exhibit habit persistence with respect to C_t^i, with habit parameter ν, and their intertemporal elasticity of substitution is γ. The objective function is

$$Max \quad E_t \sum_{k=0}^{\infty} \beta^k \left\{ \frac{\left(\tilde{C}_{t+k}^i\right)^{1-\frac{1}{\gamma}} - 1}{1 - \frac{1}{\gamma}} + \psi \frac{\left(1 - L_{t+k}^i\right)^{1-\frac{1}{\gamma}}}{1 - \frac{1}{\gamma}} + \frac{a}{1-\epsilon} \left(\frac{M_{t+k}^i}{P_{t+k}} \right)^{1-\epsilon} \right\}, \tag{1}$$

where $\tilde{C}_t^i = C_t^i - \nu C_{t-1}^i$, and where E_t is the expectation conditional on information available at time t.

Households separately accumulate capital stocks $k_t^{i,x}, \quad x = f, I, 1, 2, 3$ in the five productive sectors. Capital accumulation in each separate sector is subject to two frictions, a time-to-build feature and a Tobin's q-type quadratic adjustment cost. Under time-to-build, investment decisions made at time t require investment spending spread out over a period of 6 quarters, t to $t+5$, in order to enter the productive capital stock in period $t+6$. The shares of overall investment expenditures that need to be made in each quarter are $\omega_i, \ i = 0, 1, 2, 3, 4, 5$ ($\sum_i \omega_i = 1$). In our notation, $I_t^{i,x}$ stands for the *augmentation of the capital stock 6 quarters ahead* that is decided in period t. This decision commits the household to a pattern of actual investment spending for the current and subsequent five periods. In period t *total investment spending* $J_t^{i,x}$ in each sector x therefore equals

$$J_t^{i,x} = \omega_0 I_t^{i,x} + \omega_1 I_{t-1}^{i,x} + \omega_2 I_{t-2}^{i,x} + \omega_3 I_{t-3}^{i,x} + \omega_4 I_{t-4}^{i,x} + \omega_5 I_{t-5}^{i,x} . \tag{2}$$

Households' overall demand for investment goods is therefore

$$J_t^i = J_t^{f,i} + J_t^{I,i} + J_t^{1,i} + J_t^{2,i} + J_t^{3,i} \, .$$

Capital accumulation in each sector x then takes the form

$$k_{t+1}^{i,x} = (1-\Delta)k_t^{i,x} + I_{t-5}^{i,x} \, ,$$

where Δ is the depreciation rate. Households' decision variables at time t are the investment flows $I_t^{i,x}$ and the capital stocks 6 quarters ahead $k_{t+6}^{i,x}$. We therefore rewrite the capital accumulation equations as follows:

$$k_{t+6}^{i,x} = (1-\Delta)^6 k_t^{i,x} + (1-\Delta)^5 I_{t-5}^{i,x} + (1-\Delta)^4 I_{t-4}^{i,x} + (1-\Delta)^3 I_{t-3}^{i,x} \tag{3}$$

$$+(1-\Delta)^2 I_{t-2}^{i,x} + (1-\Delta) I_{t-1}^{i,x} + I_t^{i,x}$$

In addition to the time-to-build feature we also assume that time t investment decisions $I_t^{i,x}$ incur a quadratic adjustment cost $P_t^I \frac{\theta}{2}\left(\frac{I_t^{i,x}}{k_t^{i,x}} - \Delta\right)^2 k_t^{i,x}$. This cost has to be paid out of investment goods output,[2] and all of it is incurred in the decision period t itself. The nominal returns to capital in the five sectors x are $P_t^x r_t^x k_t^{i,x}$ (where r_t^x is the marginal product of capital), wage income is $W_t^i L_t^i$ plus a wage subsidy s_w (more on this below), and households receive equal lump-sum profit redistributions $\Pi_t^{i,x}(j)$ from monopolistically competitive producers of varieties j in all five industries x. Finally, households receive government lump sum transfers $P_t^f \tau_t^i$. Expenditure items in the household budget constraint are consumption of the final consumption good, and investment expenditures $J_t^{i,x}$ plus quadratic capital stock adjustment costs in all five industries. There are complete markets for state-contingent money claims, more specifically a complete set of contingent, one period nominal bonds maturing in $t+1$, A_{t+1}, with a period t price of $Q_{t,t+1}$. The period t budget constraint is

$$E_t\left(Q_{t,t+1}A_{t+1}^i\right) = A_t^i + M_{t-1}^i - M_t^i \tag{4}$$

$$+W_t^i L_t^i (1+s_w) + \sum_{x=f,I,1,2,3}\left[P_t^x r_t^x k_t^{i,x} + \int_0^1 \Pi_t^{i,x}(j)dj\right] + P_t^f \tau_t^i$$

$$-P_t^f C_t^i - \sum_{x=f,I,1,2,3}\left[P_t^I J_t^{i,x} + P_t^I \frac{\theta}{2}\left(\frac{I_t^{i,x}}{k_t^{i,x}} - \Delta\right)^2 k_t^{i,x}\right] \, .$$

We postpone our analysis of the labor supply decision until the next subsection, as we need to derive labor demand functions from the optimization problem of the employment agency first. For all other decision variables, households maximize (1) subject to (2), (3), and (4). The model can be used to price a variety of assets, including a risk free nominal discount bond B_{t+1}^i with nominal discount rate i_t. This interest rate is the instrument of monetary policy. We choose the initial bond holdings A_t^i so that each household has the same present discounted value of income. We also assume that each household has

2 We define $\tilde{J}_t^i$ as the sum of J_t^i and adjustment costs.

the same initial capital stock in each of the five industries. This insures that the marginal utilities of consumption, real money balances, and installed capital are equated across households, and that households' optimality conditions for all but the wage setting decision are identical. The household specific superscript can therefore be dropped in the following first order conditions. We denote the multiplier of the budget constraint (4) by Λ_t, and let $\lambda_t = \Lambda_t P_t^f$. The multiplier of the capital accumulation equations (3) is $\lambda_t q_t^x$. The final consumption good is chosen as the numeraire in what follows, so that $p_t^x = P_t^x / P_t^f$. The first-order conditions with respect to $C_t, A_t, B_t, M_t, I_t^x, k_t^x, x = f, I, 1, 2, 3,$ are then[3]

$$(C_t)^{-\frac{1}{\gamma}} - \beta\nu E_t\left(C_{t+1}\right)^{-\frac{1}{\gamma}} = \lambda_t\,, \tag{5}$$

$$Q_{t-1,t} = \tilde{\pi}_{t-1,t}\frac{\beta}{1+\pi_t^f}\frac{\lambda_t}{\lambda_{t-1}}\,, \tag{6}$$

$$\lambda_t = \beta(1+i_t)E_t\left(\frac{\lambda_{t+1}}{1+\pi_{t+1}^f}\right), \tag{7}$$

$$\frac{am_t^{-\varepsilon}}{\lambda_t} = \frac{i_t}{1+i_t}\,, \tag{8}$$

$$\begin{aligned}
&\lambda_t p_t^I \omega_0 + E_t\left[\beta\lambda_{t+1}p_{t+1}^I\omega_1 + \beta^2\lambda_{t+2}p_{t+2}^I\omega_2 + \beta^3\lambda_{t+3}p_{t+3}^I\omega_3\right. \\
&\left.+\beta^4\lambda_{t+4}p_{t+4}^I\omega_4 + \beta^5\lambda_{t+5}p_{t+5}^I\omega_5\right] + \lambda_t p_t^I\theta\left(\frac{I_t^x}{k_t^x} - \Delta\right) \\
&= \lambda_t p_t^I q_t^x + E_t\left[\beta\lambda_{t+1}p_{t+1}^I q_{t+1}^x(1-\Delta) + \beta^2\lambda_{t+2}p_{t+2}^I q_{t+2}^x(1-\Delta)^2\right. \\
&+ \beta^3\lambda_{t+3}p_{t+3}^I q_{t+3}^x(1-\Delta)^3 + \beta^4\lambda_{t+4}p_{t+4}^I q_{t+4}^x(1-\Delta)^4 \\
&\left.+\beta^5\lambda_{t+5}p_{t+5}^I q_{t+5}^x(1-\Delta)^5\right]\,,
\end{aligned} \tag{9}$$

$$\lambda_t p_t^I q_t^x = E_t\left[\beta^6\lambda_{t+6}p_{t+6}^I\left(\frac{p_{t+6}^x r_{t+6}^x}{p_{t+6}^I} + q_{t+6}^x(1-\Delta)^6 + \theta\frac{I_{t+6}^x}{k_{t+6}^x}\left(\frac{I_{t+6}^x}{k_{t+6}^x} - \Delta\right)\right)\right]. \tag{10}$$

2.2 Employment Agency and Household Labor Supply

Each household sells its labor variety L_t^i to a competitive employment agency that combines these varieties into a homogenous labor output L_t, using a CES production function with elasticity of substitution ϕ. The cost minimization problem of the employment agency is

$$\underset{L_t^i, i\in[0,1]}{Min} \int_0^1 W_t^i L_t^i di \;\; s.t.\; L_t = \left(\int_0^1 L_t^{i\,\frac{\phi-1}{\phi}} di\right)^{\frac{\phi}{\phi-1}}. \tag{11}$$

This gives rise to the set of labor demands

$$L_t^i = \left(\frac{W_t^i}{W_t}\right)^{-\phi} L_t\,, \tag{12}$$

3 $\tilde{\pi}_{t-1,t}$ is the probability of a realized event at time t conditional on the realized event at time $t-1$.

where the aggregate wage is given by

$$W_t = \left(\int_0^1 \left(W_t^i\right)^{1-\phi} di \right)^{\frac{1}{1-\phi}} . \tag{13}$$

Following Calvo (1983), it is assumed that households receive random opportunities to change their wage that follow a geometric distribution, with a probability $1 - \delta_w$ of being able to change their wage. In this respect our model of wage setting policies therefore does not differ from conventional treatments. Where it does differ is in the form of the wage setting policy that households can choose at that time. It is typically assumed that households can only choose their current wage, which then either remains constant or increases at an exogenous rate until the next reoptimization. Our model allows wage setters to choose two parameters instead of one,[4] their initial nominal wage level V_t^w and an updating rate v_t^w thereafter. Given the symmetry assumptions for households introduced earlier, all wage setters that get to reoptimize at time t will choose identical wage policies. We will nevertheless continue to use the household specific superscript i, but it now denotes a representative member of the cohort of workers that get to choose a new wage at a given time. Our assumptions mean that the time t cohort's wage at time $t + k$ is

$$W_{t+k}^i = V_t^w (1 + v_t^w)^k . \tag{14}$$

We define the 'front loading' term of the wage setting policy, i.e. the amount by which the wage setter's initial wage differs from the market aggregate wage, as $p_t^w = V_t^w / W_t$, and let $w_t = W_t / P_t^f$. In the following derivations we also need expressions for the evolution of the aggregate price index P_t^f, which is given by

$$P_{t+k}^f = P_t^f \Pi_{t,k}^f ,$$

where

$$\begin{aligned} \Pi_{t,k}^f &= 1 \text{ for } k = 0 \\ &= \prod_{s=1}^{k} (1 + \pi_{t+s}^f) \text{ for } k \geq 1 . \end{aligned} \tag{15}$$

Then the household's first-order conditions with respect to V_t^w and v_t^w are given by

$$E_t \sum_{k=0}^{\infty} (\beta \delta_w)^k \; L_{t+k}^i \left\{ \lambda_{t+k} p_t^w w_t \frac{(1 + v_t^w)^k}{\Pi_{t,k}^f} - \psi (1 - L_{t+k}^i)^{-\frac{1}{\gamma}} \right\} = 0 , \tag{16}$$

4 The model therefore imposes fewer exogenous restrictions on the optimization problem, and is thus less *ad hoc*. As mentioned in the Introduction, there is a trade-off in allowing the wage (or price) setters even more degrees of freedom – it becomes very much harder to employ standard recursive solution methods.

$$E_t \sum_{k=0}^{\infty} (\beta\delta_w)^k \; k \; L^i_{t+k} \left\{ \lambda_{t+k} p^w_t w_t \frac{(1+v^w_t)^k}{\Pi^f_{t,k}} - \psi(1-L^i_{t+k})^{-\frac{1}{\gamma}} \right\} = 0 \tag{17}$$

In deriving these conditions it was assumed that the wage subsidy s_w completely eliminates the steady state markup of wages over the marginal rate of substitution between leisure and consumption, which requires $s_w = (\phi - 1)^{-1}$. In that case these first-order conditions ensure that the real wage is equal to the marginal rate of substitution on average over the lifetime of the wage setting policy. The derivation of linearized first-order conditions for the households' problem is presented in a separate Technical Appendix.[5]

2.3 Firms

The production side of the economy consists of five sectors $x = f, I, 1, 2, 3$, three of which are intermediate input producers $\tilde{x} = 1, 2, 3$. Every sector is composed of a continuum of producers $j \in [0, 1]$ who each produce a different variety of that sector's output, and who are monopolistically competitive in their goods market. All of them have Cobb-Douglas production functions in capital, labor and (with one exception) intermediate inputs. Firms rent capital $k^x_t(j)$ from households at the competitive rental rate r^x_t and obtain labor $l^x_t(j)$ from the employment agency at the competitive nominal wage W_t. Except for intermediates producer 3, who produces a primary commodity solely with capital and labor, all other sectors also require intermediate inputs $n^x_t(j)$ produced by an upstream sector, and again firms are price takers with respect to the prices of those intermediates. Production functions are therefore

$$y^x_t(j) = (k^x_t(j))^{\alpha^k_x} \, (l^x_t(j))^{\alpha^l_x} \, (n^x_t(j))^{\alpha^n_x} \quad (\alpha^n_3 = 0)\,, \tag{18}$$

with real marginal cost equal to

$$mc^x_t = A_x \, (r^x_t)^{\alpha^k_x} \left(\frac{w_t}{p^x_t}\right)^{\alpha^l_x} \left(\frac{p^{\tilde{x}}_t}{p^x_t}\right)^{\alpha^n_x} \text{ (} \tilde{x} = 1 \text{ ,2 or 3 depending on sector),} \tag{19}$$

and with $A_x = \left(\alpha^k_x\right)^{-\alpha^k_x} \left(\alpha^l_x\right)^{-\alpha^l_x} \left(\alpha^n_x\right)^{-\alpha^n_x}$. Because all firms are competitive in their input markets they all optimally choose inputs in the same proportions. This implies that the aggregate production function of a sector x can be written as

$$\tilde{y}^x_t = (k^x_t)^{\alpha^k_x} \, (l^x_t)^{\alpha^l_x} \, (n^x_t)^{\alpha^n_x} \quad (\alpha^n_3 = 0)\,, \tag{20}$$

where $\tilde{y}^x_t = \int_0^1 y^x_t(j)dj$, $k^x_t = \int_0^1 k^x_t(j)dj$, $l^x_t = \int_0^1 l^x_t(j)dj$, $n^x_t = \int_0^1 n^x_t(j)dj$.

Final consumption goods producers sell directly to households as consumers of C_t, and final investment goods producers sell directly to households as purchasers of the overall quantity of investment goods $\tilde{J}_t$. Intermediates producers in sector 1 sell their output to either final consumption or investment goods producers. Intermediates producers in sectors 2 and 3 sell their output to intermediates producers in

[5] This is available at the author's website at http://www.stanford.edu/~kumhof/.

sectors 1 and 2. In each case the purchaser of these outputs needs to use all available varieties j, and he needs to combine them into a composite of a continuum of differentiated varieties that is produced using a CES production function with elasticity of substitution σ. We now present the solution of the purchaser's problem of choosing the cost minimizing combination of varieties j. To simplify the exposition we do so using generic notation P_t^x for prices and y_t^x for quantities demanded.[6] The overall demand for the composite is given by[7]

$$y_t^x = \left[\int_0^1 y_t^x(j)^{\frac{\sigma-1}{\sigma}} dj\right]^{\frac{\sigma}{\sigma-1}} . \tag{21}$$

The cost-minimizing set of demands is then given by

$$y_t^x(j) = \left(\frac{P_t^x(j)}{P_t^x}\right)^{-\sigma} y_t^x , \tag{23}$$

where

$$P_t^x = \left[\int_0^1 P_t^x(j)^{1-\sigma} dj\right]^{\frac{1}{1-\sigma}} . \tag{23}$$

Specifically for users of intermediate inputs, their cost minimization problem can be divided into two steps. First, they solve a sub-problem of choosing a continuum of intermediate inputs as just described, with an appropriate change of notation from P_t^x and y_t^x to the price and quantity of the intermediate input. Second, they solve the overall cost minimization problem which includes choosing the quantity of the CES composite (21) taking as given the price index (23) of that composite, again with the appropriate change of notation.

Firms in all five sectors face the same type of restrictions with respect to pricing policies that wage setters face with respect to wage setting policies. The price k periods from t for a goods variety j whose pricing policy can be changed at t is then

$$P_{t+k}^x(j) = V_t^x (1 + v_t^x)^k . \tag{24}$$

Firms discount profits expected in period $t + k$ by δ_x^k, the probability that their period t pricing policy will still be in force k periods from t, and by the k-period ahead sector specific real interest rate $R_{t,k}^x$, which is given by

$$\begin{aligned} R_{t,k}^x &= 1 \text{ for } k = 0 \\ &= \prod_{s=1}^{k} \frac{(1 + \pi_{t+s}^x)}{(1 + i_{t+s-1})} . \end{aligned} \tag{25}$$

6 For example, $c_t(j) = y_t^f(j)$. Also, define $\tilde{J}_t(j) = y_t^I(j)$.

7 Note that both the mean and log-deviation from steady state of y_t^x in (20) equals that of this output composite y_t^x, so that in linearized versions of the model we canwork with (20) replacing the former with the latter.

The government is assumed to subsidize output at the rate s_x to eliminate the steady state markup distortion of price over marginal cost. Nominal revenue at t therefore equals $P_t^x(j)y_t^x(j)(1+s_x)$. Firms' problem is to maximize

$$\underset{V_t^x, v_t^x}{Max} \quad E_t \sum_{k=0}^{\infty} \delta_x^k R_{t,k}^x y_{t+k}^x(j) \left[\frac{V_t^x(1+v_t^x)^k}{P_{t+k}^x}(1+s_x) - mc_{t+k}^x \right], \text{ s.t. (22) and (24).} \tag{26}$$

Because marginal cost is equalized across firms, all firms in a given cohort of pricesetters will behave identically. We can therefore omit firm specific superscripts except for the term $y_t^x(j)$ that identifies by j the members of a cohort that have received their price changing opportunity at the same time, and which needs to be distinguished from overall demand y_t^x. We define the front loading terms as $p_t^x \equiv V_t^x / P_t^x$. The first order condition with respect to V_t^x is then

$$p_t^x E_t \sum_{k=0}^{\infty} \delta_x^k R_{t,k}^x y_{t+k}^x(j) \frac{(1+v_t^x)^k}{\Pi_{t,k}^x} = E_t \sum_{k=0}^{\infty} \delta_x^k R_{t,k}^x y_{t+k}^x(j) mc_{t+k}^x \,, \tag{27}$$

and with respect to V_t^x we have

$$p_t^x E_t \sum_{k=0}^{\infty} \delta_x^k R_{t,k}^x k y_{t+k}^x(j) \frac{(1+v_t^x)^k}{\Pi_{t,k}^x} = E_t \sum_{k=0}^{\infty} \delta_x^k R_{t,k}^x k y_{t+k}^x(j) mc_{t+k}^x \,, \tag{28}$$

where $\Pi_{t,k}^x$ is defined as in (15). In deriving these expressions it was assumed that $s_x = (\theta-1)^{-1}$ to eliminate the markup distortion, and we therefore have $\overline{mc} = 1$.

2.4 Government

The government's fiscal policy is Ricardian. Specifically, we assume that the government budget is balanced period by period through lump-sum taxes/transfers, and that the initial stock of government bonds B_{-1} is zero. The budget constraint is therefore simply:

$$\tau_t = \frac{M_t - M_{t-1}}{P_t} - s_w w_t L_t - \sum_{x=f,I,1,2,3} s_x p_t^x y_t^x \,, \tag{29}$$

where we have used the fact that $\int_0^1 P_t^x(j) y_t^x(j) dj = P_t^x y_t^x$. We assume that the central bank pursues the following interest rate rule for its policy instrument i_t:

$$(1+i_t) = \beta^{-1}(1+\bar{\pi}) \left(\frac{E_t(1+\pi_{t+1})}{1+\bar{\pi}} \right)^{\rho} \left(\frac{y_t}{\bar{y}} \right)^{\xi} (1+h_t). \tag{30}$$

The first two components on the right hand side equal the steady state gross nominal interest rate. The central bank responds to expected deviations of inflation from its steady state and to the current output gap. Given the sectorial disaggregation of the model economy, both terms need to be defined carefully.

Real GDP in terms of final consumption goods equals consumption plus investment, because government activity is limited to transfers:

$$y_t = C_t + p_t^I y_t^I \,. \tag{31}$$

The steady state consumption share in GDP is therefore $\Omega = \bar{C}/(\bar{C} + \bar{p}^I \bar{y}^I)$. We define the the inflation rate of the GDP deflator as the weighted (by steady state spending) geometric average of CPI or final consumption goods inflation and of final investment goods inflation:

$$(1 + \pi_t) = \left(1 + \pi_t^f\right)^{\Omega} \left(1 + \pi_t^I\right)^{1-\Omega} \tag{32}$$

Finally, h_t is a zero mean autocorrelated monetary policy shock[8] with law of motion

$$\log(1 + h_t) = \rho^h \log(1 + h_{t-1}) + \log(\varepsilon_t^h). \tag{33}$$

The rule (30) can be linearized as

$$\hat{i}_t = \rho E_t \hat{\pi}_{t+1} + \theta \hat{y}_t + \hat{h}_t \,, \tag{34}$$

where $\hat{y}_t = \Omega \hat{c}_t + (1 - \Omega)(\hat{p}_t^I + \hat{y}_t^I)$ and $\hat{\pi}_t = \Omega \hat{\pi}_t^f + (1 - \Omega)\hat{\pi}_t^I$, and where $\hat{\pi}_t$ denotes the deviation from steady state of the gross inflation rate.

Such forward-looking formulations of the policy rule are fairly common in theoretical work, but in empirical work it is more common to assume one of two other formulations. One is a backward looking rule as in Rotemberg and Woodford (1998) or in Christiano, Eichenbaum and Evans (2001). The other is a forward-looking rule in inflation and output but adding a lag of the interest rate, also known as interest rate smoothing, as in Clarida, Galí and Gertler (1999). Our rule is closer to the latter but does not allow for interest rate smoothing. We replace this with the assumption that monetary policy can be characterized by persistent shocks $\hat{h}_t$, motivated by the work of Rudebusch (2002) discussed in the Introduction.

A government policy is defined as a list of stochastic processes $\{i_t, \tau_t\}_{t=0}^{\infty}$ such that, given stochastic processes $\{M_t, P_t, L_t, W_t, y_t^x, P_t^x, h_t, \ x = f, I, 1, 2, 3\}_{t=0}^{\infty}$, the conditions (29) and (30) hold for all $s \geq t$.

2.5 Equilibrium

An *allocation* is a list of stochastic processes $\{A_t, B_t, M_t, C_t, L_t^i, l_t^x(j),\ I_t^x, J_t^x, k_t^x, k_t^x(j), c_t(j), \tilde{J}_t(j), n_t^x(j), y_t^x(j), \Pi_t^x(j),\ i \in [0,1], j \in [0,1], x = f, I, 1, 2, 3\Big\}_{t=0}^{\infty}$, and a *price system* is a list of stochastic processes $\{Q_{t,t+1}, W_t, W_t^i, P_t^x, P_t^x(j), r_t^x, q_t^x,\ i \in [0,1], j \in [0,1], x = f, I, 1, 2, 3\}_{t=0}^{\infty}$.

8 Such shocks, apart from capturing deliberate decisions to deviate temporarily and possibly persistently from a systematic rule, may also represent the effects on interest rates of autocorrelated inflation forecast errors. We thank Charles Goodhart for emphasizing this point to us.

A shock process is a stochastic process $\{h_t\}_{t=0}^{\infty}$. Then equilibrium is defined as follows:

An equilibrium given initial conditions $h_{-1},\ k_{-1}^x,\ I_{-1}^x,\ I_{-2}^x,\ I_{-3}^x,\ I_{-4}^x,\ I_{-5}^x,\ P_{-1}^x,\ W_{-1}, x = f, I, 1, 2, 3,$ *is an allocation, a price system, a government policy and a shock process such that*

(a) *given the government policy, the price system and the shock process, the allocation solves the household's problem of maximizing (1) subject to (2), (3), and (4),*

(b) *given the government policy, the price system and the shock process, the allocation solves the employment agency's problem (11),*

(c) *given the government policy, the shock process, the restrictions on price setting, and the sequences* $\{P_t^x, W_t, r_t^x, y_t^x\}_{s=0}^{\infty}$*, the sequences* $\{V_t^x, v_t^x\}_{s=0}^{\infty}$ *solve firms' problem (26),*

(d) *the market for final consumption goods clears at all times,*

$$c_t(j) = y_t^f(j) \implies C_t = y_t^f\,,$$

(e) *the market for investment goods clears at all times,*

$$\tilde{J}_t(j) = y_t^I(j) \implies \sum_{x=f,I,1,2,3}\left[J_t^x + \frac{\theta k_t^x}{2}\left(\frac{I_t^x}{k_t^x} - \Delta\right)^2\right] = y_t^I\,,$$

(f) *the markets for intermediate goods clear at all times,*

$$\begin{aligned} n_t^f(j) + n_t^I(j) &= y_t^1(j) \implies n_t^f + n_t^I = y_t^1\,, \\ n_t^1(j) &= y_t^2(j) \implies n_t^1 = y_t^2\,, \\ n_t^2(j) &= y_t^3(j) \implies n_t^2 = y_t^3\,. \end{aligned}$$

(g) *the labor market clears at all times,*

$$L_t = l_t^f + l_t^I + l_t^1 + l_t^2 + l_t^3\,,$$

(h) *the market for risk-free bonds clears at all times,*

$$B_t = 0 \quad \forall t\,.$$

2.6 Price Dynamics under 2-Part Pricing Policies

The Technical Appendix contains the full derivations of linearized price and wage dynamics. Here we focus on price dynamics and give some brief intuition. The key innovation is summarized by the equation for aggregate inflation in sector x:

$$\hat{\pi}_t^x = \frac{1-\delta_x}{\delta_x}\hat{p}_t^x + \hat{\psi}_t^x . \tag{35}$$

Here $\hat{p}_t^x$ is (in deviation form) the front loading term, and $\hat{\psi}_t^x$ is the weighted average of all those past firm-specific inflation rates $\hat{v}_t^x$ that are still in force between periods $t-1$ and t, and which therefore enter into period t aggregate inflation.[9] These two components reflect the two main sources of inflation inertia. Following a monetary policy shock, the continuing effects of price updating decisions made under the old monetary policy are represented by $\hat{\psi}_t^x$, and this is the main source of inertia in aggregate inflation. In addition, if a monetary policy shock is very persistent then new price setters respond mainly through changes in their updating rates. In that case front-loading $\hat{p}_t^x$ responds very little, thereby generating further inertia. Inflation inertia implies that a persistent monetary policy shock has a much more persistent effect on the real interest rate, and on the real side this contributes significantly to output persistence.

In conventional sticky price models the dynamics of aggregate (sectorial) inflation can be summarized by just one equation, the New Keynesian Phillips Curve. In our model aggregate inflation dynamics is driven by a system of three interdependent equations, one for aggregate inflation $\hat{\pi}_t^x$, one for the updating term $\hat{v}_t^x$, and one for the inertial $\hat{\psi}_t^x$ term. While derivation of these equations is algebraically somewhat involved, the final result is straightforward and easily incorporated into dynamic stochastic general equilibrium models that can be solved with conventional solution methods.

3. Macroeconomic Dynamics

3.1 Calibration

We calibrate parameter values for the quarterly frequency. The values for the degrees of sectorial price stickiness $\delta_f = \delta_I = \delta_1 = \delta_2 = \delta_3 = \delta_w = 0.75$ imply an average contract length of four quarters, which is consistent with the empirical evidence (Taylor 1998).[10] For the personal discount factor we assume β =0.99, so that the steady state real interest rate is 4.1% per annum. With a steady state inflation rate $\bar{\pi}$ of 5% per annum we therefore have a steady state nominal interest rate of 9.1%. The intertemporal elasticity of substitution is assumed to equal γ =0.5, and the value for the habit parameter

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9 Note that in conventional Calvo (1983) style sticky price models the equivalent equation is

$$\hat{\pi}_t^x = \frac{1-\delta_x}{\delta_x}\hat{p}_t^x .$$

10 Note however that the interpretation of the empirical evidence is different under the assumptions of our model. This is because we assume that many observed price/wage changes are not associated with an updating of information about aggregate shocks. Therefore the same empirical evidence would require larger δ for our model, which would give rise to additional inflation inertia and persistence. We nevertheless adopt the conventional values.

ν =0.7 follows Boldrin, Christiano and Fisher (2001). The intratemporal elasticities of substitution between goods and between labor varieties are chosen as σ =10 and ϕ =7.7 following Chari, Kehoe and McGrattan (2002).[11] The parameter ψ is calibrated from the economy's steady state conditions assuming a proportion of time spent working in steady state of $\bar{L}$ =1/3,which is based on the evidence cited in Kydland (1995). The parameters pertaining to capital accumulation are a depreciation rate of Δ=0.025, an adjustment cost parameter of θ =10, and a set of time-to-build quarterly spending shares of $\omega_0 = \omega_5 = 1/12,\ \omega_1 = \omega_4 = 1/6,\ \omega_2 = \omega_3 = 1/4$. For the five productive sectors we assume that the intermediate inputs share in total output is 0.5 for the four sectors that employ intermediates. The share of labor in value added is assumed to equal 0.64. The parameters of the monetary policy rule and the persistence of monetary policy shocks are estimated in the following subsection. We solve the model by the algorithm of King and Watson (1997), and use impulse responses to display the dynamic response of the economy to a monetary policy shock.

3.2 Estimation of Monetary Policy Rule

We estimate the log of the monetary policy rule (30) for the US by the generalized method of moments of Hansen (1982) and Hansen and Singleton (1982). Quarterly data are used for the period 1980Q1 through 2002Q2, plus 3 lags for instruments and one lead for future inflation as a regressor. This covers the Volcker and Greenspan tenures at the Federal reserve except for the initial instruments. We limit estimation to this period as it has been argued that there was a structural break in the conduct of monetary policy at the beginning of the Volcker tenure. The data series used are the quarterly average of the annualized Federal Funds rate for i_t, the annualized quarter on quarter change in the GDP deflator for π_t, and quarterly real per capita GDP for y_t . The latter is detrended using a Hodrick Prescott filter. As instruments we use three lags each of π_t, y_t, the growth rates of the world commodity price index and of US money supply (M2), the spread between long (10–year bonds) and short (3-month TBs) US interest rates, and Hodrick-Prescott detrended real per capita consumption, real per capita investment, and real unit labor costs. The estimation attains a p-value of 0.99 and a parameter estimate for the inflation response of ρ =1.174 (t =24.02), while the output gap response coefficient ξ is statistically not significantly different from zero. We find that the time series process of the residuals of this regression can be characterized (using a Schwartz criterion) as AR(1), with coefficent ρ^h =0.735. The estimate for the latter has a standard deviation of 0.0716. We will adopt the estimated values for ρ and ξ for our calibration of the model economy, but to highlight the importance of persistent monetary policy shocks we will assume that ρ^h =0.8, i.e shock persistence is set at one standard deviation above its estimated value.

3.3 Results

The following set of impulse responses shows the effects of a monetary policy shock that leads to a 0.4% increase in the Federal Funds rate on impact. The combination of this very persistent shock and of our relatively small estimated inflation feedback coefficient in the interest rate rule contributes to a very inertial and persistent behavior of inflation and therefore of the real interest rate, but only in combination with several other key features of the model. The first is that, because our pricing specification allows price setters to change their inflation updating rate, and because with a relatively long-lived shock they have an incentive to do so, the front loading part of inflation does not respond very strongly.

[11] These authors refer to Basu and Fernald (1994, 1995), Basu (1996) and Basu and Kimball (1997) as evidence for the goods elasticity, and to Lewis (1986) as evidence for the labor elasticity.

The change of the updating rates in turn takes time to be reflected in aggregate inflation, and we get inertial and persistent inflation. This is further reinforced by a fairly slow response of both components of demand, consumption and investment, due to habit persistence and time-to-build. Their response is in turn made more persistent by the very high persistence of real interest rates, and they exhibit a hump-shaped profile, with investment responding much more strongly than consumption.

The response plots on the right hand side show the breakdown of marginal cost changes, the driving forces of inflation, into their input share weighted components. The overall response of marginal cost is moderate and slow because of the slow speed of changes in demand, but the rigidity of two of the three price components of marginal cost makes a further contribution. One is wage rigidity, and the other is rigidity in the price of upstream intermediate goods. It is here that we observe the effect of cascading nominal rigidities down the chain of intermediate goods producers. We observe that indeed the relative price[12] response and the inflation response at upstream producers is more pronounced. The effect on overall marginal cost is however muted by the flexibility of the return to capital, which is responsible for most of the sectorial level drops in marginal cost.

Overall, the qualitative behavior of this economy is very close to what one tends to get from empirical impulse responses for monetary policy shocks, but of course the way we have identified those shocks differs from most conventional treatments. We will be able to make a final judgement once the issue of how to match our model to empirical VAR impulse responses has been resolved.

4. Conclusion

This main ambition of this paper is to make further progress in enabling models with nominal rigidities to match key features of empirical impulse responses to monetary policy shocks, most notably inflation inertia and hump-shaped responses of real variables. To this end we present a theoretical model with two key advantages. First, we are able to retain the assumption of rational forward-looking price setting and can nevertheless generate significant inflation inertia. Second, the real rigidities we introduce are, we believe, not very controversial and yet are very powerful in further contributing to inertia in inflation and real interest rates, and to hump-shaped output responses. Both advantages are bought at the expense of considerable model complexity, but the model does remain sufficiently tractable and amenable to solution with standard recursive techniques.

Except for the estimation of the monetary policy rule, this paper is at this stage purely theoretical. But in qualitative terms the solutions we obtain are of the kind we expect to need in order to match the kind of empirical impulse responses that are known from the literature. That matching exercise is the subject of our current work.

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[12] Remember that the numeraire is final consumption goods.

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Figure 1. Economic Sectors and Input-Output Linkages

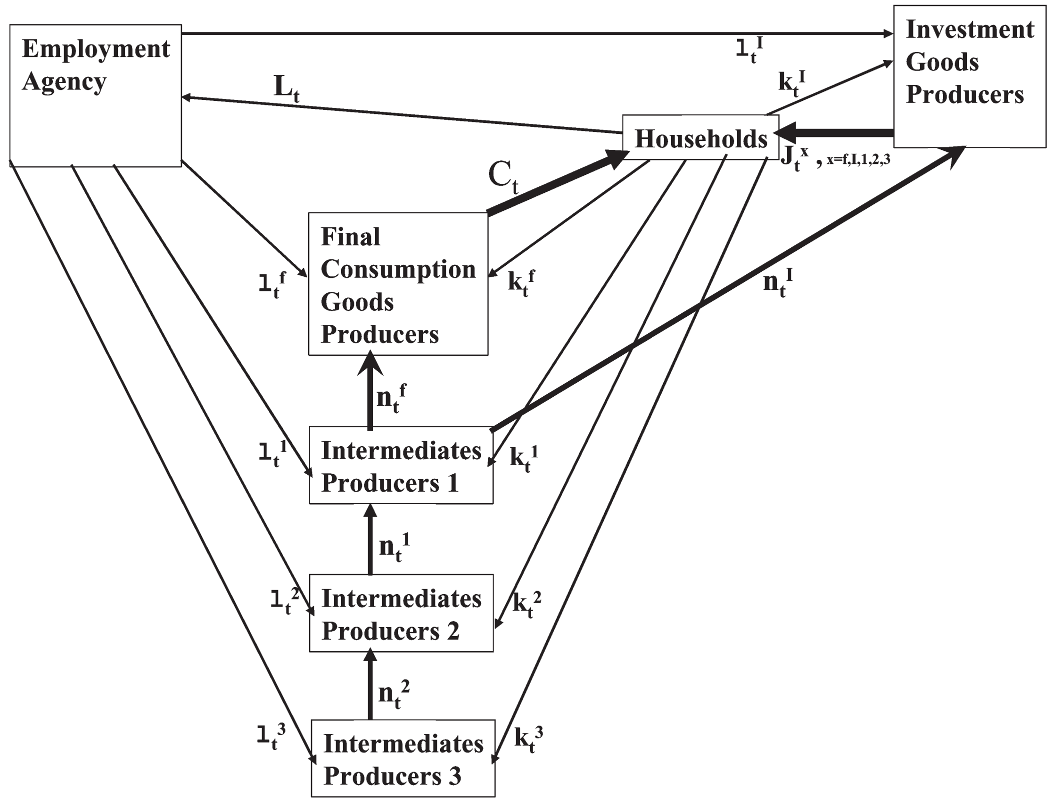

Figure 2. Impulse Responses

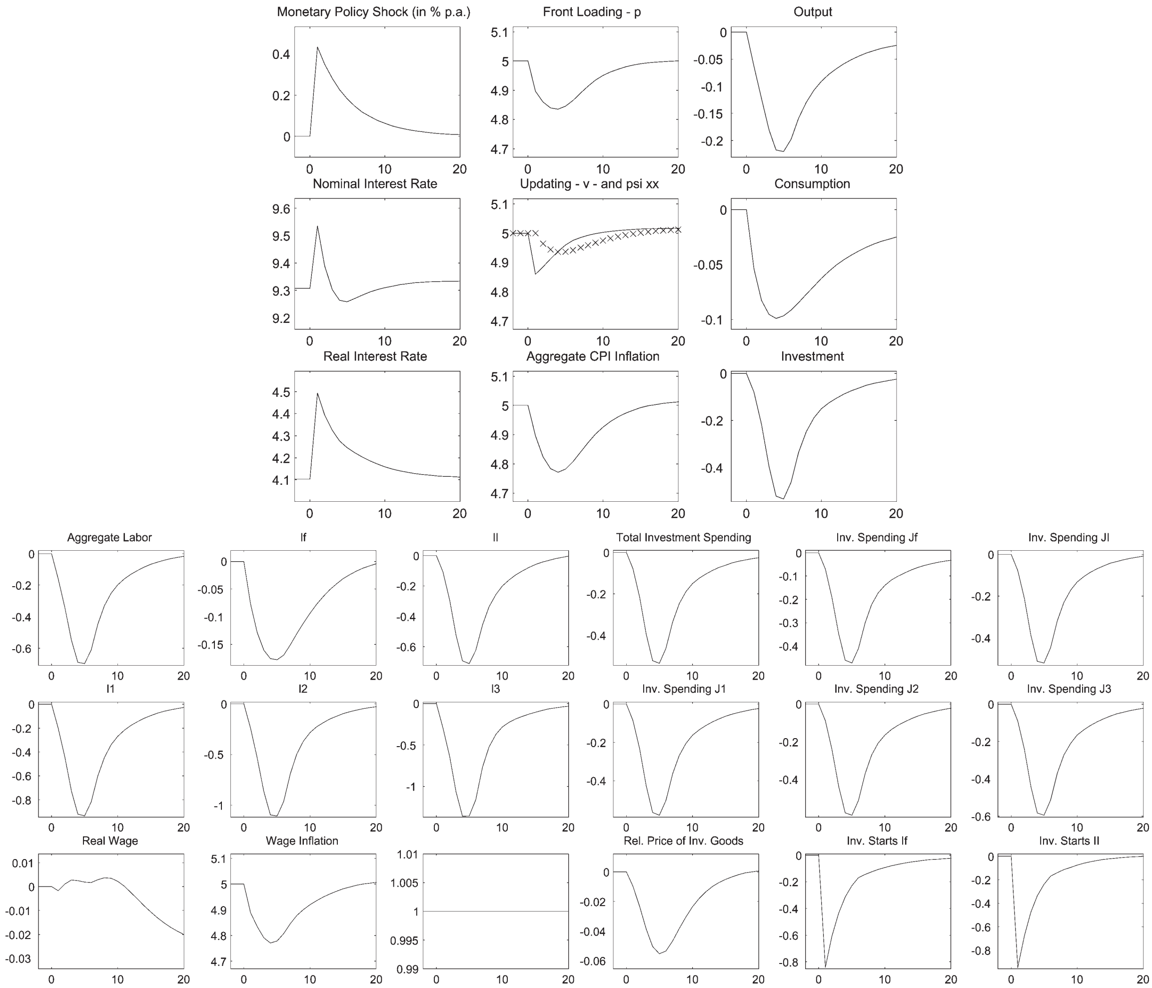

Figure 2. Impulse Responses (continued)

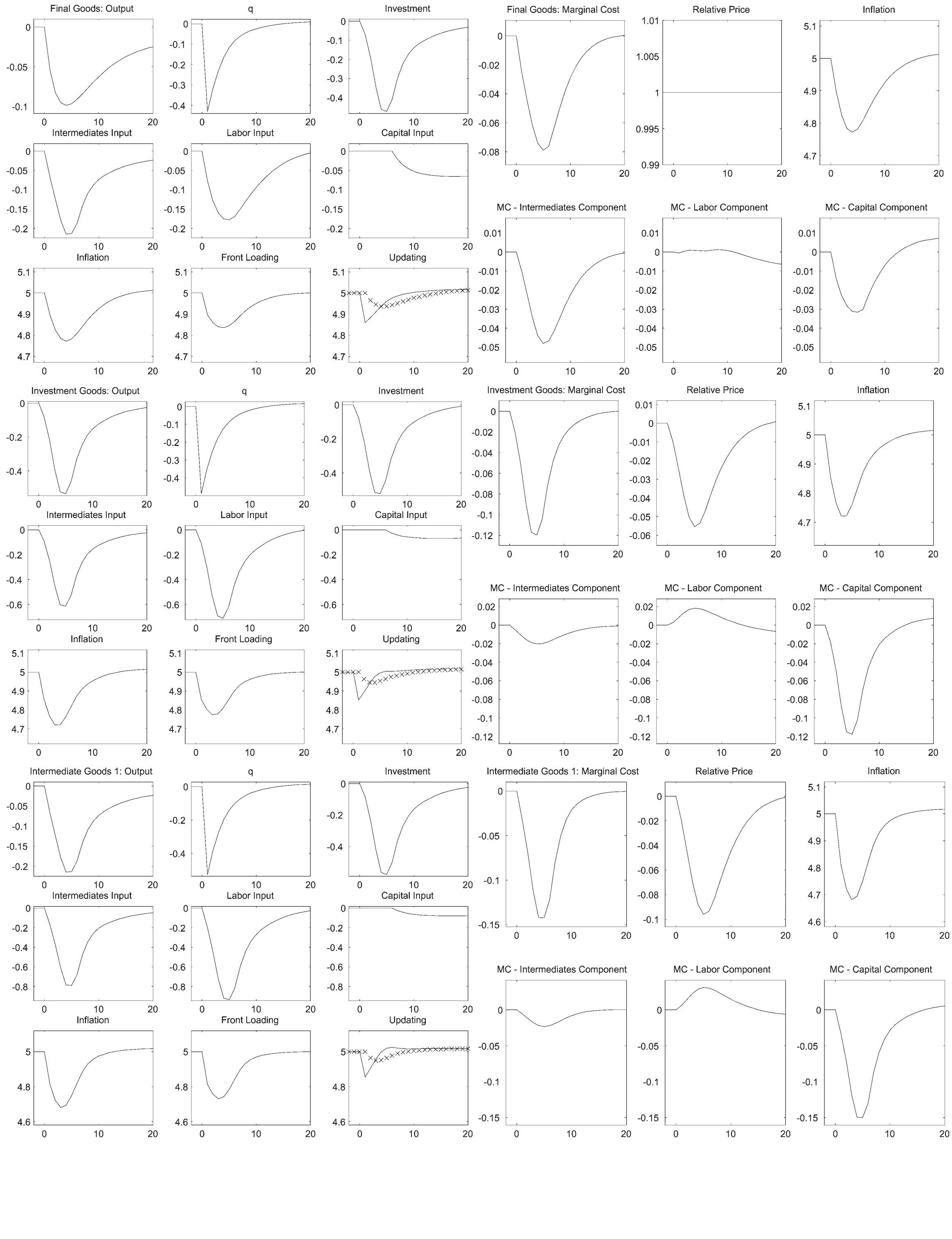

Figure 2. Impulse Responses (continued)