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Calvo vs. Rotemberg Price Setting

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# Long-run Phillips Curve and Disinflation Dynamics: Calvo vs. Rotemberg Price Setting

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## Abstract

There is widespread agreement that the two most widely used pricing assumptions in the New-Keynesian literature, i.e., Calvo and Rotemberg price-setting mechanisms, deliver equivalent dynamics. We show that, instead, they entail a very different dynamics of adjustment after a disinflation, once non linear simulations are employed. In the Calvo model disinflation implies output gains, while in the Rotemberg model a disinflation experiment implies output losses. We show that this is due to the different wedges created by the nominal rigidities in the two models: between output and hours in the Calvo model, while between output and consumption in the Rotemberg model. Moreover, unlike the Calvo model, in the Rotemberg model real wage rigidities cause a significant output slump along the adjustment path, thus restoring a dynamics in line both with the conventional wisdom and the empirical evidence.

*JEL classification:* E31, E5.

*Keywords:* Disinflation, Sticky Prices, Nonlinearities

# 1 Introduction

In this paper, we consider the standard New Keynesian framework of monopolistically competitive firms with two commonly used approaches to model firms' price-setting behavior: the Rotemberg (1982) quadratic cost of price adjustment and the Calvo (1983) random price adjustment signal. The Calvo price-setting mechanism produces relative-price dispersion among firms, while the Rotemberg model is consistent with a symmetric equilibrium. Despite the economic difference between these two pricing specifications, to a first order approximation the implied dynamics are equivalent. As shown by Rotemberg (1987) and Roberts (1995), both approaches imply the same reduced form New Keynesian Phillips curve (NKPC henceforth).<sup>1</sup> They therefore lead to observationally equivalent dynamics for inflation and output. In particular, both models deliver the well-known result of immediate adjustment of the economy to the new steady state following a disinflation, despite nominal rigidities in price-setting (see, e.g., Ball, 1994 and Mankiw, 2001). Furthermore Nisticò (2007), shows that up to a second order approximation, and provided that the steady state is efficient, both models imply the same welfare costs of inflation. Thus, they imply the same prescriptions for welfare-maximizing Central Banks. Therefore, there is widespread agreement in the literature that the two models are equivalent.

In this work, we show that it is not the case when permanent changes in the rate of inflation are considered, if one takes into account the full non-linear model. In particular, the long-run Phillips curve implied by the two models is radically different. As a consequence, the non-linear disinflation dynamics implied by the two model is also very different. As some papers have recently demonstrated (e.g. Ascari 2004, Yun 2005, Ascari and Merkl 2007) non-linearities are important because of the interaction between long-run effects and short-run dynamics in the non-linear dynamics of the model. Contrary to the common view, this interaction leads to completely different results between the implied non-linear dynamics by the Rotemberg and the Calvo price setting specifications in response to a Central Bank disinflation experiment.

Ascari and Merkl (2007) shows that non-linearities are important in shaping the adjustment dynamics following a disinflation in a Calvo price setting model. Indeed, contrary to the dynamics implied by the traditional log-linearized Calvo model, a disinflation leads to a permanently higher level

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<sup>1</sup>Kahn (2005), however, shows that even if the reduced form New Keynesian Phillips curve is the same, the impact of competition on the slope of the NKPC and on the response of inflation and output to shocks differs between the two approaches.

of output in the non-linear model, with no slump. Moreover, according to the conventional view, real wage rigidities should generate a slump in output after a credible disinflationary policy, because they prevent the immediate adjustment of inflation. However, Ascari and Merkl (2007) shows that in the non-linear Calvo model real wage rigidities increase the output during the adjustment to the new steady state. Real wage rigidities may even lead to an overshooting of the output above the new higher steady state level. A result which thus seems to be strongly at odds with the conventional view.

Unlike the Calvo model, we show that the non-linear dynamics of the Rotemberg price setting model restores results similar to the log-linear dynamics. First of all, output immediately adjust to an immediate and unexpected disinflation. Secondly, real wage rigidities imply a significant output slump along the adjustment path, restoring a conventional result on which there seems to be consensus in the literature (see, e.g., Blanchard and Galí, 2007). In sum, inferring the effects of permanent shocks through log-linearized model would not lead to big mistakes, as in the Calvo model. Therefore, the Rotemberg model seems to be more robust to non-linearities.

## 2 The model and the long-run Phillips Curve: Calvo (1983) vs. Rotemberg (1982)

In this section we briefly present a very simple and standard cashless New Keynesian model in the two version of Rotemberg and the Calvo price setting scheme. We then look at the long-run features of the two models, and in particular, at the implied long-run Phillips Curve.

### 2.1 The model

#### 2.1.1 Households and Technology

Consider an economy with a representative household which maximizes the following intertemporal separable utility function:

$$E_t \sum_{j=0}^{\infty} \beta^j \left[ \frac{C_{t+j}^{1-\sigma}}{1-\sigma} - d_n \frac{N_{t+j}^{1+\varphi}}{1+\varphi} \right] \quad (1)$$

subject to the period-by-period budget constraint

$$P_t C_t + (1 + i_t)^{-1} B_t = W_t N_t - T_t + \Pi_t + B_{t-1}, \quad (2)$$

where  $C_t$  is consumption,  $i_t$  is the nominal interest rate,  $B_t$  are one-period bond holdings,  $W_t$  is the nominal wage rate,  $N_t$  is the labor input,  $T_t$  are lump sum taxes, and  $\Pi_t$  is the profit income. The following first order conditions hold:

$$\text{Euler equation : } \frac{1}{C_t^\sigma} = \beta E_t \left[ \left( \frac{P_t}{P_{t+1}} \right) (1 + i_t) \left( \frac{1}{C_{t+1}^\sigma} \right) \right], \quad (3)$$

$$\text{Labor supply equation } \frac{W_t}{P_t} = -\frac{U_N}{U_C} = \frac{d_n N_t^\varphi}{1/C_t^\sigma} = d_n N_t^\varphi C_t^\sigma. \quad (4)$$

Final good market is competitive and the production function is given by

$$Y_t = \left[ \int_0^1 Y_{i,t}^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}}. \quad (5)$$

Final good producers demand for intermediate inputs is therefore equal to  $Y_{i,t+j} = \left( \frac{P_{i,t}}{P_{t+j}} \right)^{-\varepsilon} Y_{t+j}$ .

Intermediate inputs  $Y_{i,t}$  are produced by a continuum of firms indexed by  $i \in [0, 1]$  with the following simple technology

$$Y_{i,t} = N_{i,t}^{1-\alpha} \quad (6)$$

where labor is the only input and  $0 \leq \alpha < 1$ . The labor demand and the real marginal cost of firm  $i$  are therefore

$$N_{i,t}^d = [Y_{i,t}]^{\frac{1}{1-\alpha}}, \quad (7)$$

and

$$MC_{i,t}^r = \frac{1}{1-\alpha} \frac{W_{i,t}}{P_t} Y_{i,t}^{\frac{\alpha}{1-\alpha}}. \quad (8)$$

Note that, given the possibility of decreasing returns to labor, if  $\alpha > 0$ , then different firms charging different prices would produce different levels of output and hence have different marginal costs

$$MC_{i,t}^r = \frac{1}{1-\alpha} \frac{W_{i,t}}{P_t} \left[ \left( \frac{P_{i,t}}{P_t} \right)^{-\varepsilon} Y_{i,t} \right]^{\frac{\alpha}{1-\alpha}}. \quad (9)$$

Each firm  $i$  has monopolistic power in the production of its own variety and therefore solves a price setting problem.



### 2.1.2 Price Setting: Calvo (1983) vs. Rotemberg (1982)

#### *The Calvo model*

We will here show a generalized version of the Calvo price setting scheme, allowing for indexation. In each period there is a fixed probability  $1 - \theta$  that a firm can re-optimize its nominal price, i.e.,  $P_{i,t}^*$ . With probability  $\theta$ , instead, the firm automatically and costlessly adjust its price according to an indexation rule. The price setting problem becomes

$$\max_{\{Y_{i,t}, P_{i,t}\}_{t=0}^{\infty}} E_t \sum_{j=0}^{\infty} \beta^j \frac{\lambda_{t+j}}{\lambda_0} \theta^j \left[ \frac{P_{i,t}^* (\bar{\pi}^{\chi j})^{1-\mu} (\Pi_{t,t+j-1}^{\chi})^{\mu}}{P_{t+j}} Y_{i,t+j} - \frac{W_{t+j}}{P_{t+j}} [Y_{i,t+j}]^{\frac{1}{1-\alpha}} \right],$$

$$\text{s.t. } Y_{i,t+j} = \left[ \frac{P_{i,t}^* (\bar{\pi}^{\chi j})^{1-\mu} (\Pi_{t,t+j-1}^{\chi})^{\mu}}{P_{t+j}} \right]^{-\varepsilon} Y_{t+j} \text{ and} \quad (10)$$

$$\Pi_{t,t+j-1} = \begin{cases} \left( \frac{P_t}{P_{t-1}} \right) \left( \frac{P_{t+1}}{P_t} \right) \times \dots \times \left( \frac{P_{t+j-1}}{P_{t+j-2}} \right) & \text{for } j = 1, 2, \dots \\ 1 & \text{for } j = 0. \end{cases} \quad (11)$$

where  $\bar{\pi}$  denotes the central bank's inflation target and it is equal to the level of trend inflation. This formulation is very general, because: (i)  $\chi \in [0, 1]$  allows for any degree of price indexation; (ii)  $\mu \in [0, 1]$  allows for any degree of (geometric) combination of the two types of indexation usually employed in the literature: to steady state inflation (e.g., Yun, 1996) and to past inflation rates (e.g., Christiano et al., 2005).

In the Calvo price setting framework, firms charging prices at different periods will have different prices. In general, there will be a distribution of different prices, that is, there will be price dispersion. Price dispersion results in an inefficiency loss in aggregate production. Hence

$$N_t^d = [Y_t]^{\frac{1}{1-\alpha}} \underbrace{\int_0^1 \left[ \left( \frac{P_{i,t}}{P_t} \right)^{-\varepsilon} di \right]^{\frac{1}{1-\alpha}}}_{s_t} = [s_t Y_t]^{\frac{1}{1-\alpha}}. \quad (12)$$

Schmitt-Grohé and Uribe (2007) show that  $s_t$  is bounded below at one, so that  $s_t$  represents the resource costs due to relative price dispersion under the Calvo mechanism. Indeed, the higher  $s_t$ , the more labor is needed to

produce a given level of output. To close the model, the aggregate resource constraint is simply given by

$$Y_t = C_t. \quad (13)$$

### **The Rotemberg model**

The Rotemberg model assumes that a monopolistic firm faces a quadratic cost of adjusting nominal prices, that can be measured in terms of the final-good and given by

$$\frac{\varphi_p}{2} \left( \frac{P_{i,t}}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{i,t-1}} - 1 \right)^2 Y_t, \quad (14)$$

where  $\varphi_p > 0$  determines the degree of nominal price rigidity. As stressed in Rotemberg (1982), the adjustment cost looks to account for the negative effects of price changes on the customer-firm relationship. These negative effects increase in magnitude with the size of the price change and with the overall scale of economic activity,  $Y_t$ . Also (14) is a general specification for the adjustment cost used by, e.g., Ireland (2007), among others. This definition is the correspondent of the general specification of the Calvo price setting scheme above, within the Rotemberg one. When  $\mu = 0$  ( $\mu = 1$ ) firms find it costless to adjust their prices in line with the central bank inflation target (the previous period's inflation rate).  $\chi$  instead plays the same role of the degree of indexation in the Calvo model above.

The problem for the firm is then

$$\begin{aligned} \max_{\{Y_{i,t}, P_{i,t}\}_{t=0}^\infty} E_t \sum_{j=0}^{\infty} \beta^j \frac{\lambda_{t+j}}{\lambda_0} & \left\{ \frac{P_{i,t+j} Y_{i,t+j}}{P_{t+j}} - \frac{W_{t+j}}{P_{t+j}} [Y_{i,t}]^{\frac{1}{1-\alpha}} + \right. \\ & \left. - \frac{\varphi_p}{2} \left( \frac{P_{i,t+j}}{(\pi_{t+j-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{i,t+j-1}} - 1 \right)^2 Y_{t+j} \right\}, \\ \text{s.t. } Y_{i,t+j} &= \left[ \frac{P_{i,t+j}}{P_{t+j}} \right]^{-\varepsilon} Y_{t+j}. \end{aligned}$$

The Rotemberg model is very different from the Calvo one because there is no price dispersion. Firms can change their price in each period, subject to the payment of the adjustment cost. Therefore, all the firms face the same problem, and thus will choose the same price, producing the same quantity. In other words:  $P_{i,t} = P_t$ ,  $Y_{i,t} = Y_t$ , and  $MC_{i,t}^r = MC_t^r = \frac{1}{1-\alpha} \frac{W_t}{P_t} Y_t^{\frac{\alpha}{1-\alpha}}$ ,  $\forall i$ . Contrary to the Calvo scheme, thus, the aggregate production function features no inefficiency due to price dispersion, that is

$$Y_t = N_t^{1-\alpha} \quad (15)$$

Indeed, in the Rotemberg model, the adjustment cost enters the aggregate resource constraint that is given by

$$Y_t = C_t + \frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{t-1}} - 1 \right)^2 Y_t, \quad (16)$$

Note that this creates an inefficiency wedge between output and consumption:

$$Y_t \left[ 1 - \frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{t-1}} - 1 \right)^2 \right] = C_t \quad (17)$$

This is the main difference between the Calvo and the Rotemberg model. In the former one, the cost of nominal rigidities, i.e., price dispersion, creates a wedge between aggregate employment and aggregate output, making aggregate production less efficient. In the Rotemberg model, instead, the cost of nominal rigidities, i.e., the adjustment cost, creates a wedge between aggregate consumption and aggregate output, because part of the output goes in the price adjustment cost.

## 2.2 The long-run Phillips Curve

### *The Calvo (1983) model*

This section looks at the steady state of the two models, and in particular at the implications for the long-run Phillips Curve.

- Figure 1 about here -

Figure 1 shows the long-run relationship between inflation and output in the standard Calvo model with no indexation (i.e.,  $\chi = 0$ ).<sup>2</sup> As well-known (e.g., Ascari 2004, Yun 2005), the long-run Phillips Curve is negatively sloped: positive long-run inflation reduce output, because it increases price dispersion. Higher price dispersion acts as a negative productivity shift, because  $Y = \left(\frac{N}{s}\right)^{1-\alpha}$ . Thus, the steady state real wage lowers with trend inflation, and so does consumption and leisure, so that actually steady state employment increases. As a consequence, steady state welfare decreases.

<sup>2</sup>We consider the following rather standard parameters specification (see Section 3):  $\sigma = 1$ ,  $\beta = 0.99$ ,  $\varepsilon = 10$ ,  $\phi = 1$ ,  $\theta = 0.75$ ,  $\alpha = 0$  and  $\chi = 0$ . However, none of the results qualitatively depends on the parameters values.

To be more precise, actually, the derivative of the long-run Phillips Curve evaluated at zero inflation, i.e., the tangent at zero inflation of the curve depicted in Figure 1, is positive. Indeed, this positive slope equals the positive long-run relationship between inflation and output implied by the standard log-linear New Keynesian Phillips Curve popularized by Woodford (2003) among others. The positive slope is due to what Graham and Snower (2004) call the "time discounting effect": in setting the new price, firms discount the future, where nominal prices are higher because of trend inflation. Hence, the average mark-up decreases with trend inflation. However, the relationship between steady state mark-up (and thus output) and inflation is non-linear. The effects of non-linearities due to price dispersion are quite powerful and turn up very quickly, inverting the relationship from positive to negative.<sup>3</sup>

### *The Rotemberg (1982) model*

The Appendix shows that the long-run Phillips Curve in the Rotemberg model is equal to

$$Y = \left[ \frac{\frac{\varepsilon-1}{\varepsilon} + \frac{(1-\beta)}{\varepsilon} \varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}}{\frac{d_n}{(1-\alpha)} \left(1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2\right)^\sigma} \right]^{\frac{1-\alpha}{\varphi+\sigma+\alpha(1-\sigma)}}. \quad (18)$$

It follows immediately that (if  $\beta < 1$ )

$$\exists \bar{\pi}^* < 1 \quad s.t. \quad \begin{cases} \bar{\pi} > \bar{\pi}^* \implies \frac{dY}{d\bar{\pi}} > 0 \\ \bar{\pi} = \bar{\pi}^* \implies \frac{dY}{d\bar{\pi}} = 0 \\ \bar{\pi} < \bar{\pi}^* \implies \frac{dY}{d\bar{\pi}} < 0 \end{cases}.$$

Note that this implies that  $\bar{\pi} \geq 1 \implies \frac{dY}{d\bar{\pi}} > 0$ , so that the minimum of output occurs at negative rate of steady state inflation, unless  $\beta = 1$ . This is a "time discounting effect", in the same logic of the one described above: in changing the price, a firm would weight relatively more today adjustment cost of moving away from yesterday price, than the tomorrow adjustment cost of fixing a new price away from the today's one. As in the Calvo model, the discounting effect tends to reduce average mark-up. But unlike the Calvo model, there is no price dispersion that interact with

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<sup>3</sup>Graham and Snower (2004) call these effects "employment cycling" (product cycling for sticky prices) and "labor supply smoothing" (production smoothing for sticky prices) effects. See also King and Wolman (1996).

trend inflation, and thus this is the only effect of trend inflation on the price setting decision. Indeed, the steady state mark-up is given by

$$markup = \left[ \frac{\varepsilon - 1}{\varepsilon} + \frac{(1 - \beta)}{\varepsilon} \varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x} \right]^{-1} \quad (19)$$

which is monotonically decreasing in  $\bar{\pi}$ , for positive trend inflation ( $\bar{\pi} > 1$ ). The fact that the mark-up decreases with trend inflation makes output to increase with trend inflation. However, a fraction of output is not consumed, but it is eaten up by the adjustment cost. As evident from (17), the adjustment cost is increasing in trend inflation, and so is the wedge between output and consumption. The higher trend inflation, the more output is produced, but the less is consumption. Opposite to the Calvo model, then, output is increasing with trend inflation, but, as in the Calvo model, employment is increasing, while consumption and welfare are decreasing with trend inflation (see Figure 2)<sup>4</sup>.

- Figure 2 about here -

As we will see in the next section, the opposite slope of the long-run Phillips Curve between the two models determines a very different short-run adjustment in the non-linear dynamics following a permanent shift in the central bank inflation target.

### 3 Temporary vs. permanent shock

In this section we look at two monetary policy experiments: 1) a *temporary* negative shock to the inflation target; 2) an unanticipated and *permanent* reduction in the inflation target of the Central Bank. The Central Bank follows a standard Taylor rule, with the weight  $\alpha_\pi$  on deviations of inflation from the target level and the weight  $\alpha_y$  on output deviations, i.e.,

$$\left( \frac{1 + i_t}{1 + \bar{i}} \right) = \left( \frac{\pi_t}{\bar{\pi}} \right)^{\alpha_\pi} \left( \frac{Y_t}{\bar{Y}} \right)^{\alpha_y}. \quad (20)$$

We consider the following parameters specification, as in Ascari and Merkl (2007):  $\sigma = 1$ ,  $\phi = 1$ ,  $\beta = 0.99$ ,  $\varepsilon = 10$ ,  $\varphi_p = 100$ ,  $\theta = 0.75$ ,  $\alpha = 0$  and

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<sup>4</sup>As in Ireland (2007), we set the cost of adjusting prices  $\varphi_p = 100$ , to generate a slope of the log-linear Phillips curve equal to 0.10.

$\chi = 0$ . Since the monetary authority implements the standard Taylor (1993) rule, we set  $\alpha_\pi = 1.5$  and  $\alpha_y = 0.5$ . None of the qualitative results and of the arguments in the paper depends on the calibration values chosen.<sup>5</sup>

### 3.1 Temporary Shock

We now consider the dynamics of the two non linear models after a 1% temporary negative shock to the inflation target  $\bar{\pi}$ . We set the autoregressive parameter of the shock to  $\rho = 0.5$ . We plot the impulse response functions (IRFs henceforth) of output, inflation, nominal interest rate, real wages and consumption, assuming 4% trend inflation.

#### *The Calvo model*

Figure 3 displays the IRFs to a 1% temporary negative shock to the inflation target  $\bar{\pi}$  when the model is based on the Calvo staggered price-setting. A negative temporary shock to the inflation target is followed by a monetary tightening that causes a slump in output and a temporary reduction in inflation, real wages, consumption and hours.

- Figure 3 about here -

#### *The Rotemberg model*

Figure 4 shows the IRFs for the same policy experiment in the case of the Rotemberg model. Also in this case a negative temporary shock to the inflation target is followed by a monetary tightening. The increase in the nominal interest rate induces a fall in output and a temporary reduction in inflation, real wages, consumption and hours.

- Figure 4 about here -

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<sup>5</sup>Figures 1-8 are obtained using the software DYNARE developed by Michel Juillard and others at CEPREMAP, see <http://www.cepremap.cnrs.fr/dynare/>. The paths in the Figures correspond to deterministic simulations, since they display the movement from a deterministic steady state to another one. DYNARE solves for these paths by stacking up all the equations of the model for all the periods in the simulation (which we set equal to 100). Then the resulting system is solved en bloc by using the Newton-Raphson algorithm, by exploiting the special sparse structure of the Jacobian blocks. The non-linear model thus is solved in its full-linear form, without any approximation.

Figures 3 and 4 therefore show that the two different price adjustment mechanisms deliver a very similar dynamics in response to a temporary shock to the inflation target. The IRFs do not differ qualitatively and the quantitative differences are almost marginal. Moreover, the adjustment dynamics to a temporary shock is not sensitive to non-linearities, in the sense that is not affected by the level of trend inflation, especially in the case of Rotemberg model. Results are different when we consider a permanent shock to the inflation target.

### 3.2 Permanent Shock

We now look at an unanticipated and permanent reduction in the inflation target of the Central Bank. We plot the path for output, inflation, nominal interest rate, real wages, consumption and hours in response to such a change in the Central Bank policy regime. We consider three cases: a disinflation from 4%, 6% and 8% to zero.

#### *The Calvo model*

As shown by Ascari and Merkl (2007), when nonlinear simulations are employed, the adjustment path of the Calvo model is completely different from the one obtained with the log-linear model. Unlike in the log-linear model, a disinflation experiment increases the permanent steady state level of output. In figure 5 we plots the response of the main economic variables to a disinflation for the three different initial values of trend inflation. Output increases sluggish to the new higher steady state level. Moreover, the higher is the initial value of trend inflation (i.e. the higher is the shock) the more sluggish is the transition of the variables to the new steady state level. Since output is entirely consumed, consumption and output show the same adjustment path.

Note, instead, the adjustment dynamics in hours worked. Hours jump on impact, because output increases. Moreover, there is an additional effect that spurs hours, coming from price dispersion, i.e.,  $s$ . The lower price dispersion, so the less the hours that are needed for a given increase in output. For all the cases considered, price dispersion decreases monotonically to the new lower steady state level. This is why hours thus peak on impact, and then start decreasing. Indeed, along the adjustment, output is increasing, while price dispersion is decreasing. From period 2 onwards, the latter effect then dominates, making aggregate production more efficient and saving hours worked, despite the rise in output. Note that the permanent decrease of price dispersion can be interpreted as a permanent increase in

labor productivity, that in turn permanently increases the real wage. Real wages behavior also depend on the dynamics of hours, and thus on the joint dynamics of output and price dispersion. The adjustment in real wages roughly follow the behavior of hours, showing however an hump shape and overshooting their new higher real long-run equilibrium level.

The Calvo model then implies that output and consumption closely move together, while output and hours move in opposite directions during the adjustment, after the impact period. As explained in Section 2.1.2, inflation in the Calvo model creates a wedge between aggregate employment and aggregate output, through price dispersion. The long-run gain of a disinflation comprises the decrease in this wedge, inducing a short-run dynamics that reduces the gap between output and hours, by increasing output and reducing hours worked, thus increasing labor productivity and the real wage.

- Figure 5 about here -

### ***The Rotemberg model***

When prices are set à la Rotemberg, even if nonlinear simulations are employed, the economy would immediately adjust to the new steady state. This is a first important difference between the Rotemberg and the Calvo model, and it is entirely due to price dispersion. The Calvo model implies price dispersion, i.e.,  $s_t$ , that is a backward-looking variable that adjusts sluggishly after a disinflation. Thus, the non-linear solution of the model must keep track of this state variable, and the model dynamics is inertial. The Rotemberg, instead, is symmetric, and thus it does not feature any price dispersion. Thus, the non-linear version of the simple New Keynesian model above with Rotemberg pricing is completely forward-looking. The economy, hence, jumps immediately in the new steady state without any transitional dynamics.<sup>6</sup>

A second important difference regards the long-run effects and the adjustment dynamics of the variables. With Rotemberg pricing, a disinflation

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<sup>6</sup>Note that this would be the case also for the standard *log-linear* version of the New Keynesian model with Calvo pricing (e.g., Woodford, 2003). Indeed, if log-linearized around a zero inflation steady state, then price dispersion would not matter for the model dynamics up to first-order. Moreover, if, instead, one assumes full indexation to trend inflation, i.e.,  $\gamma = 0$  and  $\chi = 1$ , then both the log-linear and the non-linear model with Calvo pricing would imply immediate adjustment after a disinflation, as the Rotemberg model. Indeed, in case of full indexation, there is no price dispersion in steady state, whatever the value of trend inflation. So nothing prevents the model to jump to the new steady state, since price dispersion in this case does not have to adjust.



causes a drop in output. The higher the shock, the higher is the increase in firms' markup and the larger is the fall of output. As a consequence, the fraction of output wasted for adjusting prices is lower. This is the reason why consumption increases to the new higher steady state instead of decreasing, as happens in the Calvo model. Hours and the real wage jump downward on impact to the new lower steady state value.

The Rotemberg model then implies that output and hours closely jump together, while output and consumption move in opposite directions on impact. Exactly the opposite of the Calvo model. As explained in Section 2.1.2, inflation in the Rotemberg model creates a wedge between aggregate consumption and aggregate output, through the adjustment cost. The long-run gain of a disinflation comprises the decrease in this wedge, by increasing consumption, while output falls.

- Figure 6 about here -

We therefore show that, when the economy is hit by a permanent and unanticipated inflation target shock, the two nonlinear models, based on the two different price setting mechanisms, show very different and opposite dynamics.

### 3.3 Real Wage Rigidities: Effects on Disinflation Dynamics

Recently some authors suggest that real wage rigidities is an important feature that restores realistic output cost of disinflation in a Calvo model (e.g., Blanchard and Galí, 2007). Ascari and Merkl (2007), instead, show that studying the non-linear dynamics of the model, real wage rigidities actually create a boom in output, rather than a slump. Indeed, Ascari and Merkl (2007) assume the following partial adjustment model for real wage in order to introduce real wage rigidities à la Hall (2005)

$$\frac{W_t}{P_t} = \left( \frac{W_{t-1}}{P_{t-1}} \right)^\gamma MRS_t^{1-\gamma}, \quad (21)$$

where  $MRS$  is the marginal rate of substitution between labor supply and consumption. For sufficiently high value of  $\gamma$ , the model implies a sluggish adjustment of real wages. Figure 7 replicates Ascari and Merkl (2007) experiment in the Calvo price setting model. Real wage rigidities have a rather surprising implication on the economy dynamics when a disinflation experiment is implemented: they may lead to an overshooting of the output

above its new permanent natural level. The higher the values of  $\gamma$ , the more likely is the overshooting of output.

- figure 7 about here -

The intuition is straightforward. As we saw in section 3.2, without real rigidities a disinflation leads to a short-run overshooting of the real wage over its new higher long-run value. Real wage rigidities, instead, causes a sluggish adjustment in the real wage, which therefore can not overshoot on impact. The real wage is thus lower along the adjustment, and this spurs output. Real wage rigidities, thus, transfer the overshooting from the real wage to output.

When firms set their price à la Rotemberg the result is the other way round, restoring conventional wisdom. Figure 8 shows that sluggish real wages cause an output slump along the adjustment path. The slump of output becomes more significant the higher the parameter of real wage rigidities,  $\gamma$ .

- figure 8 about here -

To give an intuition for these results, again we need to look at the interplay between long-run effects and the short-run dynamic adjustment in the nonlinear models. Unlike the Calvo model, in the Rotemberg model a disinflation implies an immediate adjustment to a permanently lower level of output, hours and real wage. Real wage rigidities again prevent the immediate adjustment of the real wage, that sluggishly decreases towards the new lower long-run level. Hence, the higher the real wage rigidities, the higher is the real wage along the adjustment, and this depresses output. Hence, contrary to the Calvo model, the Rotemberg model exhibits a dynamics in line both with the conventional wisdom and the empirical evidence: real wage rigidities cause a significant output slump along the adjustment path, and therefore they imply a significant trade-off between stabilizing inflation and output (see, e.g., Blanchard and Galí, 2007).

### 3.4 Rotemberg model and consumption dynamics

As shown in the previous sections in the standard Rotemberg model, the cost of nominal rigidities, i.e., the adjustment cost, creates a wedge between aggregate consumption and aggregate output, because part of the output goes in the price adjustment cost, that represents a pure waste for the economy. As a consequence, when the economy is hit by a negative permanent shock to the inflation target, output co-moves with hours while consumption goes in the opposite direction.

This last result seems to be at odds with empirical findings, but it could be easily fixed by assuming that the adjustment costs are rebated to consumers. As in the standard model,  $\frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^x)^\mu (\bar{\pi}^x)^{1-\mu} P_{t-1}} - 1 \right)^2 Y_t$  is a cost for the intermediate good producing firm and therefore it lowers firms profits  $\Pi_t$ . If we now assume that the cost of adjusting prices is paid to the representative consumer, then,  $\frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^x)^\mu (\bar{\pi}^x)^{1-\mu} P_{t-1}} - 1 \right)^2 Y_t$  enters the household budget constraint increasing her revenues. When markets clear the household budget constraint becomes:  $C_t = \frac{W_t N_t}{P_t} + \frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^x)^\mu (\bar{\pi}^x)^{1-\mu} P_{t-1}} - 1 \right)^2 Y_t + \Pi_t$ . Therefore, substituting for the representative firms profits,  $\Pi_t$ ,<sup>7</sup> it is straightforward to find that the aggregate resource constraint implies that the entire output is consumed, that is,  $C_t = Y_t$ . The Appendix shows that under this assumption, the long-run Phillips Curve is still positively sloped, but the long-run effects of inflation on output are substantially lower than in the standard Rotemberg model, since nothing is wasted for adjusting prices. Under this assumption, output co-moves both with hours and consumption, so a disinflation would cause an immediate drop in output, consumption and hours. Finally, the introduction of real wage rigidities still causes a significant output slump along the adjustment path, and a similar path for both hours and consumption.

## 4 Conclusion

This paper considers disinflation dynamics in a New Keynesian model with two firms' price-setting mechanisms: the Rotemberg (1982) quadratic cost of price adjustment and the staggered price setting introduced by Calvo (1983).

<sup>7</sup>The real profits of the representative firms are given by:  $\Pi_t = Y_t - \frac{W_t N_t}{P_t} - \frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^x)^\gamma (\bar{\pi}^x)^{1-\gamma} P_{t-1}} - 1 \right)^2 Y_t$ .

We show that, when non linear simulation are employed, the interaction between long-run effects and short-run dynamics leads to completely different results under the two price settings specifications. If the Central Bank permanently and credibly reduces the inflation target, the Calvo model implies output gain, rather than cost, of disinflation. In the Rotemberg model, instead, output immediately adjust to the new lower steady state. We show that this discrepancy is due to the different wedges that the cost of nominal rigidities creates in the two models. Moreover, in the Calvo model, a high degree of real wage rigidities delivers the odd result of an overshooting of output above its new higher steady state level. On the contrary, in the Rotemberg model, sluggish real wages cause a significant output slump along the adjustment path. This last result restores a conventional result on which there seems to be consensus in the literature (see, e.g., Blanchard and Galí, 2007).

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## 6 Technical Appendix

### 6.1 Household

Given the separable utility function

$$U(C_t(h), N_t(h)) = \frac{C_t^{1-\sigma}}{1-\sigma} - d_n \frac{N_t^{1+\varphi}(h)}{1+\varphi}, \quad (22)$$

subject to the budget constraint

$$P_t C_t + (1 + i_t)^{-1} B_t = W_t N_t - T_t + \Pi_t + B_{t-1}, \quad (23)$$

where  $i_t$  is the nominal interest rate,  $B_t$  are one-period bond holdings,  $W_t$  is the nominal wage rate,  $N_t$  is the labor input,  $T_t$  are lump sum taxes, and  $\Pi_t$  is the profit income. The representative consumer maximizes the expected discounted (using the discount factor  $\beta$ ) intertemporal utility subject to the budget constraint (23), yielding the following first order conditions:

*Labor supply equation:*

$$\frac{W_t}{P_t} = -\frac{U_N}{U_C} = \frac{d_n N_t^\varphi}{1/C_t^\sigma} = d_n N_t^\varphi C_t^\sigma. \quad (24)$$

We introduce real wage rigidities in the same way as Blanchard and Galí (2007), that is

$$\frac{W_t}{P_t} = \left(\frac{W_{t-1}}{P_{t-1}}\right)^\gamma MRS_t^{1-\gamma} = \left(\frac{W_{t-1}}{P_{t-1}}\right)^\gamma \left(-\frac{U_{N_t}}{U_{C_t}}\right)^{1-\gamma}, \quad (25)$$

hence

$$\frac{W_t}{P_t} = \left(\frac{W_{t-1}}{P_{t-1}}\right)^\gamma (d_n N_t^\varphi C_t^\sigma)^{1-\gamma}. \quad (26)$$

*Euler equation:*

$$\frac{1}{C_t^\sigma} = \beta E_t \left[ \left(\frac{P_t}{P_{t+1}}\right) (1 + i_t) \left(\frac{1}{C_{t+1}^\sigma}\right) \right] \quad (27)$$

### 6.2 Technology

Final good producers use the following technology

$$Y_t = \left[ \int_0^1 Y_{i,t}^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}}. \quad (28)$$

Their demand for intermediate inputs is therefore equal to

$$Y_{i,t} = \left( \frac{P_{i,t}}{P_t} \right)^{-\varepsilon} Y_t. \quad (29)$$

The production function of the intermediate good producers is instead given by:

$$Y_{i,t} = N_{i,t}^{1-\alpha}. \quad (30)$$

### 6.3 The Rotemberg model

#### 6.3.1 Firm's pricing

Each firm  $i$  has monopolistic power in the production of its own variety and therefore has leverage in setting the price. In doing so it faces a quadratic cost of adjusting nominal prices, measured in terms of the finished goods and given by:

$$\frac{\varphi_p}{2} \left( \frac{P_{i,t}}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{i,t-1}} - 1 \right)^2 Y_t, \quad (31)$$

where  $\varphi_p > 0$  is the degree of nominal price rigidity. This relationship, as stressed in Rotemberg (1982), looks to account for the negative effects of price changes on customer-firm. These negative effects increase in magnitude with the size of the price change and with the overall scale of economic activity,  $Y_t$ . Similarly to Ireland (2007) we denote  $\bar{\pi}$  the central bank's inflation target.  $\pi_{t-1} = \frac{P_{t-1}}{P_{t-2}}$  is the aggregate inflation level in the previous period. The parameter  $\mu$  lies between zero and one:  $1 \geq \mu \geq 0$ . This means that the extent to which price setting is backward looking or adjust in line with trend inflation depends on whether  $\mu$  is closer to zero or one. When  $\mu = 0$  firms find it costless to adjust their prices in line with the central bank inflation target. When  $\mu$  is equal to 1 firms find it costless to adjust their prices in line with the previous period's inflation rate.  $\chi$  instead plays the same role of the degree of indexation in the Calvo model.

The problem for the firm is to choose  $\{P_t(i), N_t(i)\}_{t=0}^\infty$  in order to maximize its total market value given by,

$$\max_{\{N_{i,t}, P_{i,t}\}} \frac{\Pi_{i,t}}{P_{i,t}} = E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left\{ -\frac{\varphi_p}{2} \left( \frac{P_{i,t}}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{i,t-1}} - 1 \right)^2 \frac{Y_t}{P_t} \right\},$$



subject to the demand constraint for each variable (29) and to (30). Let define  $MC_t^r$  as the lagrangian multiplier of the production function. The following first order condition with respect to labor holds:

$$\begin{aligned}\frac{W_{i,t}}{P_t} &= (1 - \alpha) MC_{i,t}^r N_{i,t}^{-\alpha} \\ &= (1 - \alpha) MC_{i,t}^r \frac{Y_{i,t}}{N_{i,t}} \\ &= (1 - \alpha) MC_{i,t}^r Y_{i,t}^{-\frac{\alpha}{1-\alpha}},\end{aligned}$$

therefore real marginal costs can be written as:

$$MC_{i,t}^r = \frac{1}{1 - \alpha} \frac{W_{i,t}}{P_t} Y_{i,t}^{\frac{\alpha}{1-\alpha}}. \quad (32)$$

The first order condition for the optimal price setting is given by,

$$\begin{aligned}&\frac{\lambda_t}{\lambda_0} \left[ (1 - \varepsilon) \left( \frac{P_{i,t}}{P_t} \right)^{-\varepsilon} \frac{Y_t}{P_t} - \varphi_p \left( \frac{P_{i,t}}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_{i,t-1}} - 1 \right) \frac{Y_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_{i,t-1}} \right] + \\ &+ \frac{\lambda_t}{\lambda_0} MC_{i,t}^r \varepsilon \left( \frac{P_{i,t}}{P_t} \right)^{-(\varepsilon+1)} \frac{Y_t}{P_t} + \\ &+ \beta E_t \frac{\lambda_{t+1}}{\lambda_0} \varphi_p \left( \frac{P_{i,t+1}}{(\pi_t^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_{i,t}} - 1 \right) \frac{Y_t P_{i,t+1}}{(\pi_t^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_{i,t}^2} = 0.\end{aligned}$$

Imposing the symmetric equilibrium we get

$$\begin{aligned}&1 - \varphi_p \left( \frac{P_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_{t-1}} - 1 \right) \frac{P_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_{t-1}} + \\ &+ \varphi_p \beta E_t \left( \frac{\lambda_{t+1}}{\lambda_t} \right) \left[ \left( \frac{P_{t+1}}{(\pi_t^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_t} - 1 \right) \frac{P_{t+1}}{(\pi_t^\chi)^\mu (\bar{\pi}\chi)^{1-\mu} P_t} \frac{Y_{t+1}}{Y_t} \right] \\ &= (1 - MC_t^r) \varepsilon,\end{aligned} \quad (33)$$

or

$$\begin{aligned}&1 - \varphi_p \left( \frac{\pi_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}\chi)^{1-\mu}} - 1 \right) \frac{\pi_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}\chi)^{1-\mu}} + \\ &+ \varphi_p \beta E_t \left( \frac{C_{t+1}}{C_t} \right)^{-\sigma} \left[ \left( \frac{\pi_{t+1}}{(\pi_t^\chi)^\mu (\bar{\pi}\chi)^{1-\mu}} - 1 \right) \frac{\pi_{t+1}}{(\pi_t^\chi)^\mu (\bar{\pi}\chi)^{1-\mu}} \frac{Y_{t+1}}{Y_t} \right] \\ &= (1 - MC_t^r) \varepsilon.\end{aligned} \quad (34)$$

### 6.3.2 Aggregation

The aggregate resource constraint is now simply given by

$$Y_t = C_t + \frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{t-1}} - 1 \right)^2 Y_t, \quad (35)$$

$$\text{or } Y_t = \left( 1 - \frac{\varphi_p}{2} \left( \frac{P_t}{(\pi_{t-1}^\chi)^\mu (\bar{\pi}^\chi)^{1-\mu} P_{t-1}} - 1 \right)^2 \right)^{-1} C_t.$$

The aggregate production function hence is

$$Y_t = N_t^{1-\alpha}. \quad (36)$$

The aggregate real marginal costs are

$$MC_t^r = \frac{1}{1-\alpha} \frac{W_t}{P_t} Y_t^{\frac{\alpha}{1-\alpha}}.$$

### 6.3.3 Steady State

The deterministic steady state is obtained by dropping the time indices. The steady state inflation is equal to the Central Bank inflation target:  $\pi = \bar{\pi}$ .

The aggregate resource constraint implies

$$C = \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right) Y, \quad (37)$$

from the aggregate production function

$$N = Y^{\frac{1}{1-\alpha}}, \quad (38)$$

and from real marginal costs

$$MC^r = \frac{1}{1-\alpha} \frac{W}{P} Y^{\frac{\alpha}{1-\alpha}}, \quad (39)$$

$$\text{or } \frac{W}{P} = (1-\alpha) MC^r Y^{-\frac{\alpha}{1-\alpha}}.$$

Equation (34) becomes

$$(1 - \varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}) + \varphi_p \beta [(\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}] = (1 - MC_t^r) \varepsilon, \quad (40)$$

then solving for the steady state value of aggregate real marginal costs yields

$$MC^r = \frac{\varepsilon - 1}{\varepsilon} + \frac{(1-\beta)}{\varepsilon} \varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}. \quad (41)$$

The markup, defined as  $\frac{1}{MC^r}$ , is therefore

$$markup = \left[ \frac{\varepsilon - 1}{\varepsilon} + \frac{(1 - \beta)}{\varepsilon} \varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x} \right]^{-1},$$

and the labor supply equation is

$$\frac{W}{P} = d_n N^\varphi C^\sigma, \quad (42)$$

both in the case of flexible and real wage rigidity. Euler Equation gives

$$1 + \bar{i} = \frac{1}{\beta}. \quad (43)$$

(36), (39) and (42) imply

$$(1 - \alpha) MC^r Y^{-\frac{\alpha}{1-\alpha}} = d_n Y^{\frac{\varphi}{1-\alpha}} Y^\sigma C^\sigma,$$

substituting the aggregate resource constraint, (37),

$$(1 - \alpha) MC^r Y^{-\frac{\alpha}{1-\alpha}} = d_n Y^{\frac{\varphi}{1-\alpha}} Y^\sigma \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma,$$

or

$$\begin{aligned} MC^r &= \frac{d_n}{(1 - \alpha)} Y^{\frac{\varphi}{1-\alpha}} Y^\sigma Y^{\frac{\alpha}{1-\alpha}} \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma \\ &= \frac{d_n}{(1 - \alpha)} Y^{\frac{\varphi + \sigma + \alpha(1-\sigma)}{1-\alpha}} \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma. \end{aligned}$$

Combine it with real marginal costs in (41)

$$\frac{\varepsilon - 1}{\varepsilon} + \frac{(1 - \beta)}{\varepsilon} \varphi_p (\bar{\pi}^{1-x} - 1) \frac{\bar{\pi}}{\bar{\pi}^x} = \frac{d_n}{(1 - \alpha)} Y^{\frac{\varphi + \sigma + \alpha(1-\sigma)}{1-\alpha}} \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma,$$

and then solve for  $Y$

$$Y = \left[ \frac{\frac{\varepsilon-1}{\varepsilon} + \frac{(1-\beta)}{\varepsilon} \varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}}{\frac{d_n}{(1-\alpha)} \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma} \right]^{\frac{1-\alpha}{\varphi + \sigma + \alpha(1-\sigma)}}, \quad (44)$$

to get the steady state level of output.

Note that with Calvo price setting the steady state output is <sup>8</sup>

$$Y = \left( x^{1+\frac{\varepsilon\alpha}{1-\alpha}} \left( \frac{\varepsilon-1}{\varepsilon} \right) \frac{\left( 1 - \theta\beta\bar{\pi}^{\frac{\varepsilon}{1-\alpha}} \right)}{\frac{1}{1-\alpha}d_n s^\varphi (1 - \theta\beta\bar{\pi}^{\varepsilon-1})} \right)^{\frac{1-\alpha}{\varphi+\sigma+\alpha(1-\sigma)}}.$$

We now consider the case in which price adjustment costs are rebated to consumers. Market clearing conditions imply that the steady state household budget constraint can be written as:

$$C = \frac{WN}{P} + \left( \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right) Y + \Pi \quad (45)$$

firms steady state profits are given by:

$$\Pi = Y - \frac{WN}{P} - \left( \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right) Y \quad (46)$$

therefore, substituting (46) in (45) we get the steady state aggregate resource constraint which is,

$$C = Y, \quad (47)$$

the steady state level of output becomes:

$$Y = \left[ \frac{\frac{\varepsilon-1}{\varepsilon} + \frac{(1-\beta)}{\varepsilon}\varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}}{\frac{d_n}{(1-\alpha)}} \right]^{\frac{1-\alpha}{\varphi+\sigma+\alpha(1-\sigma)}} \quad (48)$$

### 6.3.4 The Long run Phillips Curve in the Rotemberg model

$$Y = \left[ \frac{\frac{\varepsilon-1}{\varepsilon} + \frac{(1-\beta)}{\varepsilon}\varphi_p (\bar{\pi}^{1-x} - 1) \bar{\pi}^{1-x}}{\frac{d_n}{(1-\alpha)} \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma} \right]^{\frac{1-\alpha}{\varphi+\sigma+\alpha(1-\sigma)}}, \quad (49)$$

Define:  $a \equiv \frac{\varepsilon-1}{\varepsilon}$ ,  $b \equiv \frac{(1-\beta)}{\varepsilon}\varphi_p$ ,  $c \equiv \frac{d_n}{(1-\alpha)}$ ,  $d \equiv \frac{1-\alpha}{\varphi+\sigma+\alpha(1-\sigma)}$ , which are constants independent of the steady state inflation rate  $\bar{\pi}$ . Then

$$\begin{aligned} \frac{d}{d\bar{\pi}} \left( \left[ \frac{a+b(\bar{\pi}^{1-x}-1)\bar{\pi}^{1-x}}{c\left(1-\frac{\varphi_p}{2}(\bar{\pi}^{1-x}-1)^2\right)^\sigma} \right]^d \right) &= \frac{d}{d\bar{\pi}} \left( Y(\bar{\pi})^d \right) \\ &= d[Y(\bar{\pi})]^{d-1} \frac{b(2(1-x)\bar{\pi}^{1-2x} - (1-x)\bar{\pi}^{-x}) + \sigma \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^{-1} (\varphi_p (\bar{\pi}^{1-x} - 1)(1-x)\bar{\pi}^{-x})}{c \left( 1 - \frac{\varphi_p}{2} (\bar{\pi}^{1-x} - 1)^2 \right)^\sigma} \end{aligned}$$

<sup>8</sup>For a complete derivation of the Calvo model see Ascari and Merkl (2007).

$$= d[Y(\bar{\pi})]^{d-1} \frac{b(1-\chi)\bar{\pi}^{-\chi}(2\bar{\pi}^{1-\chi}-1)+\sigma\left(1-\frac{\varphi_p}{2}(\bar{\pi}^{1-\chi}-1)^2\right)^{-1}(\varphi_p(\bar{\pi}^{1-\chi}-1)(1-\chi)\bar{\pi}^{-\chi})}{c\left(1-\frac{\varphi_p}{2}(\bar{\pi}^{1-\chi}-1)^2\right)^\sigma}$$

This expression implies:

-  $\chi = 1 \implies \frac{dY}{d\bar{\pi}} = 0$

-  $\bar{\pi} \geq 1 \implies \frac{dY}{d\bar{\pi}} > 0$ , so that the minimum of output occurs at negative rate of steady state inflation, unless  $\beta = 1$ , that implies  $b = 0$ .

If  $\beta < 1$ , then

$$- \exists \pi^* < 1 \text{ s.t. } \begin{cases} \bar{\pi} > \pi^* \implies \frac{dY}{d\bar{\pi}} > 0 \\ \bar{\pi} = \pi^* \implies \frac{dY}{d\bar{\pi}} = 0 \\ \bar{\pi} < \pi^* \implies \frac{dY}{d\bar{\pi}} < 0 \end{cases}$$

## 7 Figures

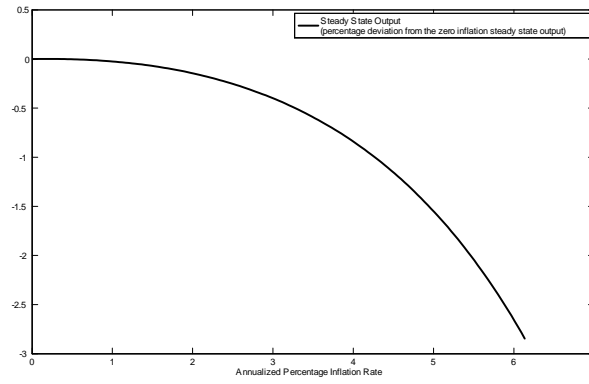


Figure 1. Long-run Phillips Curve in the Calvo model

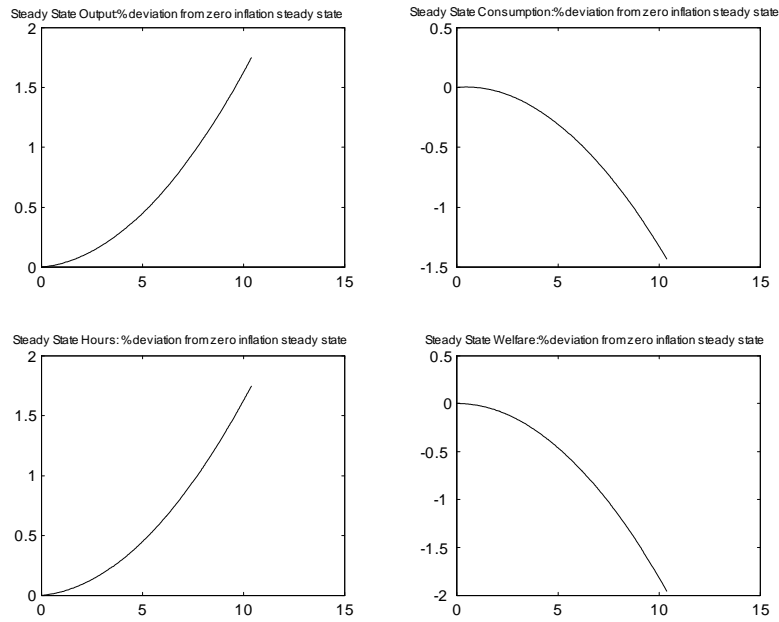


Figure 2. Steady state in the Rotemberg model

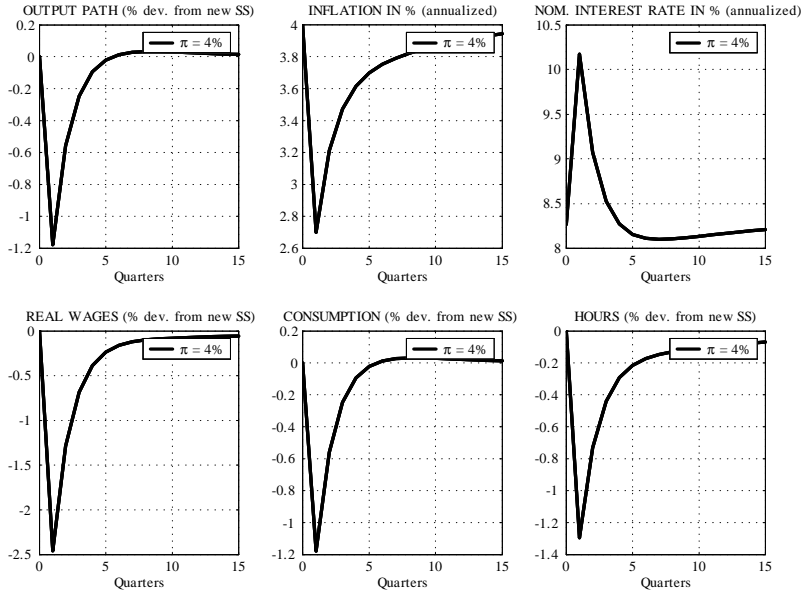


Figure 3. Temporary Shock to the Calvo Model

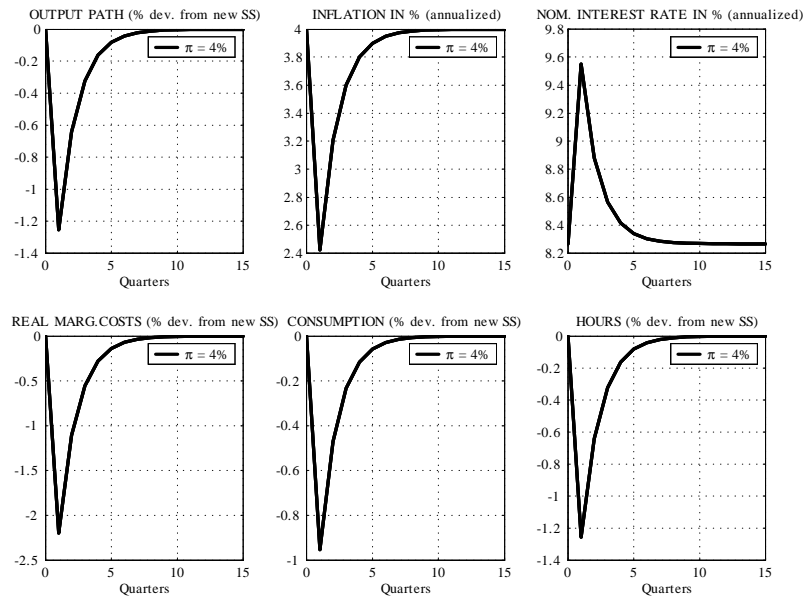


Figure 4. Temporary Shock to the Rotemberg Model

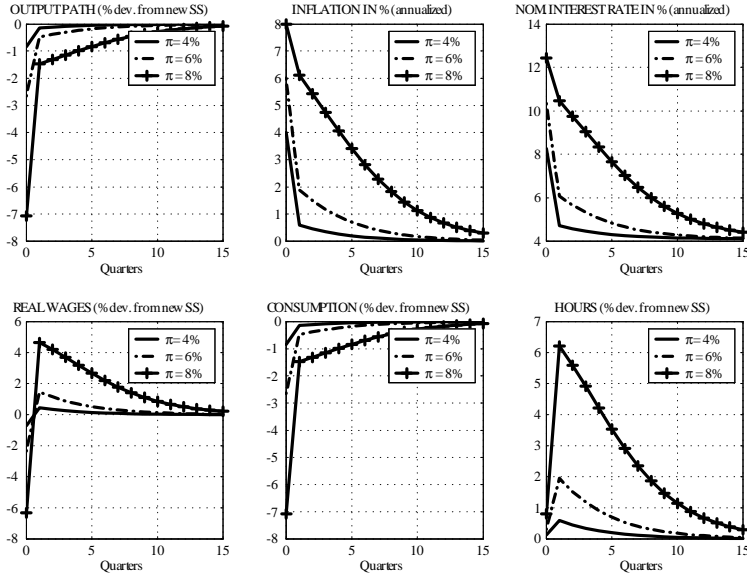


Figure 5. Permanent shock to the Calvo model

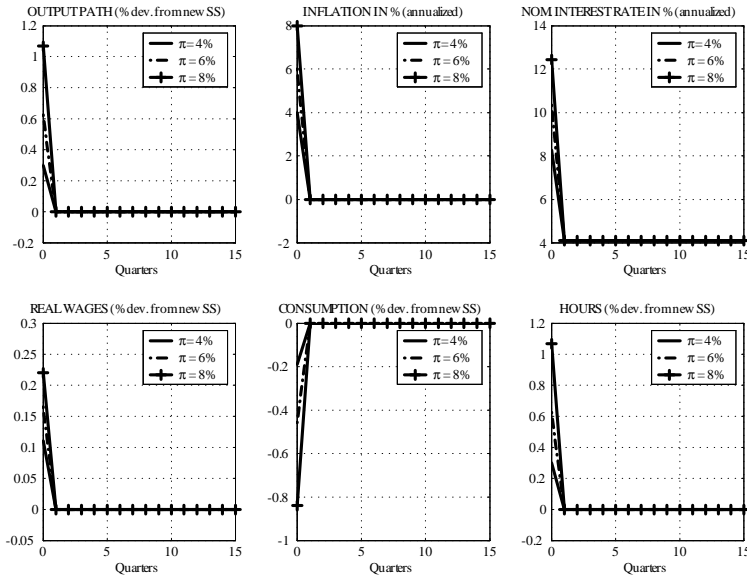


Figure 6. Permanent shock to the Rotemberg model



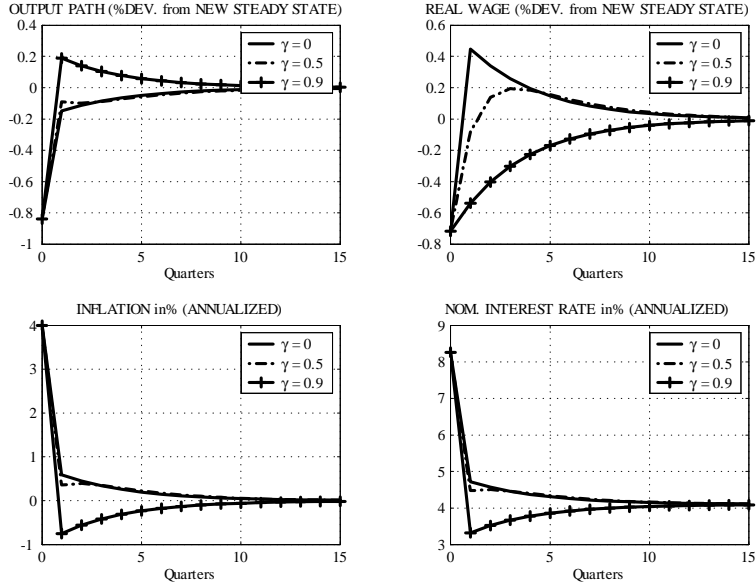


Figure 7. Permanent shock to the Calvo model with real wage rigidity

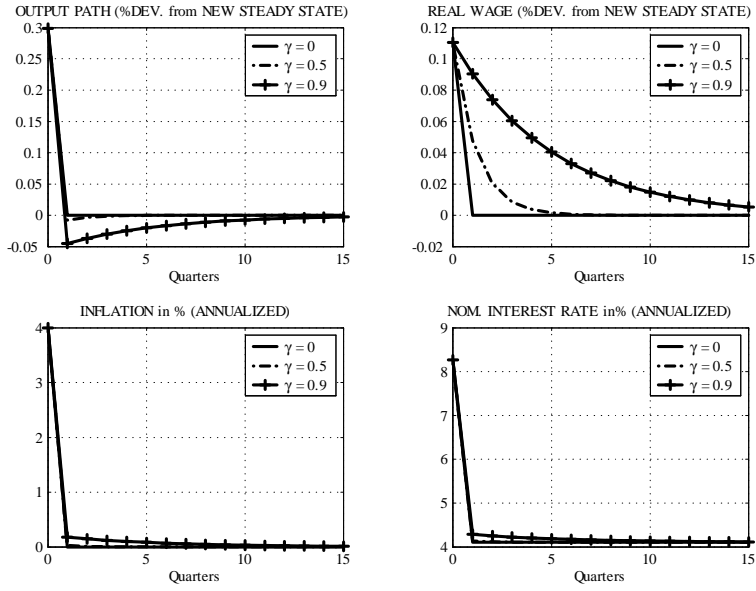


Figure 8. Permanent shock to the Rotemberg model with real wage rigidity

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