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PRICE SETTING AND THE STEADY-STATE EFFECTS OF INFLATION

BY MIGUEL CASARES

May 2002

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Address	**Kaiserstrasse 29**
	D-60311 Frankfurt am Main
	Germany
Postal address	**Postfach 16 03 19**
	D-60066 Frankfurt am Main
	Germany
Telephone	**+49 69 1344 0**
Internet	**http://www.ecb.int**
Fax	**+49 69 1344 6000**
Telex	**411 144 ecb d**

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Abstract

This paper examines how price setting plays a key role in explaining the steady-state effects of inflation in a monopolistic competition economy. Three pricing variants (optimal prices, indexed prices, and unchanged prices) are introduced through a generalization of the Calvo-type setting that allows the possibility of price indexation, i.e., prices may be adjusted by the rate of inflation. We found that in an economy with less indexed prices the steady-state negative impact of inflation on output is higher. In the extreme case without no price indexation at all (purely Calvo-type economy), unrealistically heavy falls in capital and output were reported when steady-state inflation increases. Regarding welfare analysis, our results support a long-run monetary policy aimed at price stability with a close-to-zero inflation target. This finding is robust to any price setting scenario.

Keywords: price setting, superneutrality, welfare cost of inflation.

JEL classification: E13, E31, E50.

Non-technical summary

This working paper studies the implications of having different price setting behavior in a monopolistic competition economy. Three ways of deciding prices are introduced: optimal prices (when the price is set by solving an optimizing problem), indexed prices (when the price is automatically increased by the rate of inflation), and unchanged prices (when the price remains constant for the coming period). We will considered a constant fraction of producers using each of these three alternatives for price setting. Then, our objective will be to analyze the effects in the long-run of having higher inflation in the economy. Our results show that there is a negative long-run relationship between inflation and output for any pricing distribution. Moreover, the impact of higher inflation on output is larger when a higher fraction of prices remain unchanged.

1 Introduction

The purpose of this paper is to study the impact of different pricing specifications in the steady-state analysis of inflation. Our framework will be a closed-economy optimizing monetary model with monopolistic competition. The steady-state solution will be computed and will then be altered by its rate of inflation under several price setting variants.

Following early contributions by Hicks (1935), Baumol (1952) and Sidrauski (1967), most optimizing monetary models coincide in featuring a money demand based upon the role of money as a medium of exchange.[1] Money is employed by economic agents as a means of facilitating daily transactions. More explicitly, a transaction costs function can be incorporated into the model with real money balances as one of its arguments. Here we will follow this argument by including a shopping time technology as in McCallum and Goodfriend (1987).

In this paper, producers will decide prices in a standard monopolistic competition setup. Price rigidities arise when market circumstances prevent producers from choosing their optimal price. Specifically, we begin by taking the pricing scheme described in the seminal paper by Calvo (1983), now widespread in the literature, i.e., producers can set a new price optimally only under some fixed probability. This setting has been recently criticized by Wolman (1999) because the probability of optimal price adjustment should not be independent of the number of periods without adjustment. Besides, a substantial fraction of producers stay for a considerable number of periods without making price changes.[2]

Taking this criticism into consideration, we introduce two alternatives among producers who cannot price optimally. They will either maintain the price unchanged (as in the original Calvo setup), or adjust the price by raising it by the long-run rate of inflation (the price indexation scheme). The choice between indexing the price or keep it unchanged is exogenously determined by a fixed probability. As a result, there are three types of prices in the economy: optimal, indexed, and unchanged. The distribution of producers according to their price setting behavior will be defined when calibrating the probabilities on both price stickiness and price indexation.

The rationale for price indexation is based on the presence of high evaluation costs to determine the optimal price (information costs, processing costs, computational costs,...).[3] If these costs are

[1] There are two approaches to demand analysis that recognize only the store-of-value role of money, namely, the portfolio approach of Tobin (1958) and the overlapping generations approach of Wallace (1980). Since these ignore the medium-of-exchange function, they imply that no money would be demanded if there were other assets (of equal riskiness) yielding positive interest earnings to their holders.

[2] In addition, there are a number of papers that emphasize the difficulties of replicating some of the business cycle features of modern economies by using a New-Keynesian Phillips curve based on the Calvo price setting specification. Two representative works are Fuhrer and Moore (1995), and Mankiw (2001).

[3] Christiano, Eichenbaum, and Evans (2001) have already put forth this argument in their model and cite a paper

high the price indexation rule may be the best mechanism to set prices. Moreover, the behavior implied by the price indexation rule turns out to be the optimal one on a steady-state basis and therefore the average losses that it will entail would not appear excessive.

As for the decision to maintain the price unchanged, it may come about because of the existence of menu costs.[4] Dotsey, King, and Wolman (1999) find in a state-dependent model with fixed costs to changing prices that more producers will adjust prices when the rate of inflation rises. Without endogenizing pricing behavior in this paper, we will calculate the welfare losses associated with maintaining prices in a more inflationary economy. This might be compared with some measure of menu costs in order to decide whether or not to use price indexation, and thus endogenize the price indexation behavior.

The study of the long-term effects of inflation and its welfare cost in optimizing monetary models has received much attention in the last few years (recent contributions include Dotsey and Ireland (1996), Wolman (1997), Chadha, Haldane and Janssen (1998), Wu and Zhang (2000), and Lucas (2000)). Most of the papers give welfare cost of inflation figures relative to the Friedman rule rate (Friedman (1969)), as they claim that Friedman's result is applicable in optimizing monetary models. However when price rigidities are considered in a monopolistic competition-type model, the Friedman rule rate may not imply maximum welfare on a steady state basis. This point has been investigated by King and Wolman (1996, 1999), and by Khan, King, and Wolman (2000) and will also receive some attention in this paper.

As for the organization of the rest of the paper, section 2 describes the model. Section 3 is devoted to determining the transmission mechanisms from nominal to real variables in steady state. Next, calibration is carried out in section 4. Section 5 deals with the implications of several price setting scenarios in the steady-state analysis of inflation. Section 6 concludes the paper by stressing the main results obtained.

2 An optimizing model with sticky prices and price indexation

Let the economy contain a continuum of alike households indexed by $i \in [0,1]$. The preferences of the representative infinitely-lived household, at a moment of time t, are expressed in an intertemporal utility function whose arguments are a consumption index c and leisure time l

$$E_t \left[\sum_{j=0}^{\infty} \beta^j U\left(c_{t+j}, l_{t+j}\right) \right] \tag{1}$$

by Zbaracki et al. (2000) to provide some empirical evidence supporting it.

[4] Menu costs should be defined in a very broad sense so as to include the direct costs of re-labelling together with all the indirect costs associated to new prices (information costs, consumers dislike, adjustment costs,...).

where the discount factor is $\beta = \frac{1}{1+\rho}$, with $\rho > 0$ representing the rate of time preference. The rational expectation operator in period t is denoted by $E_t[.]$ and it proceeds by taking into consideration all the information available for that period. We assume positive first derivatives and negative second derivatives of the instantaneous utility function with respect to both consumption and leisure ($U_c > 0$, $U_l > 0$, $U_{cc} < 0$, and $U_{ll} < 0$). In addition, we assume no cross marginal effects ($U_{cl} = 0$).

Consumption units are an aggregate of many goods. Indices were chosen for both consumption and the aggregate price level as in Dixit and Stiglitz (1977):

$$\begin{array}{l} c_t = \left[\int_0^1 c_t(i)^{\frac{\theta-1}{\theta}} di\right]^{\frac{\theta}{\theta-1}} \\ P_t^A = \left[\int_0^1 P_t(i)^{1-\theta} di\right]^{\frac{1}{1-\theta}} \end{array}, \ with \ \ \theta > 1. \tag{2}$$

Households are also producers. In period t, the household production function $f(n_t^d, k_t)$ gives the amount produced, y_t, depending on the stock of capital, k_t, undertaken from the previous production, and on the quantity of labor demanded, n_t^d. In particular, a Cobb-Douglas technology represents the production possibilities shared by all the households

$$y_t = f(n_t^d, k_t) = \left[n_t^d\right]^{1-\alpha} [k_t]^{\alpha}, \tag{3}$$

with $0 < \alpha < 1$. This technology shows decreasing marginal returns on both labor ($f_{nn} < 0$) and capital ($f_{kk} < 0$), positive cross-marginal productivity ($f_{nk} > 0$), and exhibits constant returns to scale. Households decide how much to produce according to the Dixit-Stiglitz demand function[5]

$$f(n_t^d, k_t) = \left[\frac{P_t}{P_t^A}\right]^{-\theta} y_t^A, \tag{4}$$

in which the amount of output depends negatively on the selling price P_t, and positively on the Dixit-Stiglitz aggregate price level P_t^A, and on the Dixit-Stiglitz aggregate output $y_t^A = \left[\int_0^1 y_t(i)^{\frac{\theta-1}{\theta}} di\right]^{\frac{\theta}{\theta-1}}$.

Trading needs arise from the separability between what is produced (single good) and what is consumed (multiple goods) by the household. In this scenario, households can take advantage of monetary services when carrying out transactions as they may save some transaction costs. They have at their disposal a time-cost transactions technology that captures the transaction

[5] We are implicitly assuming that any household could also produce the aggregate output good by using the Dixit-Stiglitz output aggregator technology defined in the text. If so, the maximizing profits criterion leads to the demand equation (4), and the zero-profit condition leads to the Dixit-Stiglitz price level definition introduced in (2).

costs depending on the level of consumption and the amount of real money balances:[6]

$$s_t = s(c_t, m_t), \tag{5}$$

where s_t is the time devoted to shopping (so-called "shopping time") in period t. The first and second order derivatives have the signs $s_c > 0$, $s_m < 0$, $s_{cc} > 0$, $s_{mm} > 0$, and $s_{cm} < 0$. The transactions-facilitating property of money as a medium of exchange is represented through the signs $s_m < 0$ and $s_{cm} < 0$, which imply that the use of more monetary services reduces the total and marginal transactions costs.

Thus, in period t households will split their total time T between work, leisure, and shopping

$$T = n_t^s + l_t + s_t, \tag{6}$$

where n_t^s is the labor supply in period t. The budget constraint to be held in period t by the representative household expressed in aggregate output units is

$$\frac{P_t}{P_t^A} y_t + g_t = c_t + k_t - (1-\delta)k_{t-1} + w_t(n_t^d - n_t^s) + m_t - (1+\pi_t)^{-1} m_{t-1} + (1+r_t)^{-1} b_t - b_{t-1}, \tag{7}$$

where g_t are government lump-sum transfers, δ is the capital depreciation rate, w_t is the real wage, π_t is the rate of inflation, and r_t is the real interest rate.

Income is raised from two sources: the aggregate output value of production sold in the market $\frac{P_t}{P_t^A} y_t$, and net lump-sum real transfers from the government g_t. Income is spent on consumption goods c_t, on investment $k_t - (1-\delta)k_{t-1}$, on payments for net labor hired $w_t(n_t^d - n_t^s)$, on increasing the demand for real money holdings $m_t - (1+\pi_t)^{-1} m_{t-1}$, and on net purchases of government bonds $(1+r_t)^{-1} b_t - b_{t-1}$. The following definitions were used for real money balances, inflation, and the real interest rate:

$$m_t = \frac{M_t}{P_t^A}, \tag{8}$$

$$\pi_t = \frac{P_t^A}{P_{t-1}^A} - 1, \tag{9}$$

$$1 + r_t = \frac{1 + R_t}{1 + E_t \pi_{t+1}}, \tag{10}$$

where R_t is the nominal interest rate. In addition, the nominal money growth rate, μ_t, is defined as follows

$$\mu_t = \frac{M_t}{M_{t-1}} - 1. \tag{11}$$

[6] Alternatively, there could exist an output-cost transactions technology in which transaction costs would be measured in terms of output and would enter the budget constraint (see Casares (2000) for a survey on optimizing monetary models).

Without loss of generality, it is assumed that both monetary and fiscal policies are conducted by applying a constant rule on money growth and lump-sum real transfers respectively

$$\mu_t = \mu, \quad (12)$$

$$g_t = g. \quad (13)$$

The lump-sum transfers of the government are financed either by increasing the money supply or by selling bonds to the households. In turn, the government budget constraint becomes in aggregate output terms

$$g_t = m_t - (1+\pi_t)^{-1} m_{t-1} + (1+r_t)^{-1} b_t - b_{t-1}. \quad (14)$$

The optimal choices of the representative household in period t are those that solve the optimizing dynamic problem which involves deciding c_t, k_t, n_t^d, n_t^s, l_t, m_t, b_t, and P_t so as to maximize (1) while satisfying the sequence of current and expected future budget, time, and Dixit-Stiglitz demand constraints.[7]

The selling price P_t is subject to the market conditions *à la* Calvo, i.e., each producer can set the optimal price only with a probability equal to $1-\eta$. Those producers who cannot optimize the selling price will have two alternatives. First, under a constant probability equal to χ, they will increase the price by the long-run rate of inflation. Thus, a fraction $\eta\chi$ of producers will adjust their price following the indexation rule $P_t = (1+\pi)P_{t-1}$ with π denoting the steady-state rate of inflation. Second, they will leave the price unchanged with a probability $1-\chi$. In other words, the fraction $\eta(1-\chi)$ of the households will set $P_t = P_{t-1}$.[8]

The price indexation rule $P_t = (1+\pi)P_{t-1}$ was chosen because it is consistent with the optimal dynamic pricing decision in a time-evolving steady state. The reason behind this is that in steady state both optimal and indexed prices grow at the steady-state rate of inflation, π.[9]

Aggregate variables and the overall resources constraint.

[7] The behavioral equations of this households-as-producers model are equivalent to those obtained when firms were considered as separate entities producing and selling their differentiated good in a monopolistic competition market. They would hire labor and rent capital from the households in competitive markets. The maximizing-profit criterion would lead to the same first order conditions for the selling price, the demand for labor, and the demand for capital.

[8] Examples of models using such a non-optimal pricing scheme are Yun (1996), and Erceg *et al.* (2000). For the steady state purposes of this paper, the price adjustment rule selected would be equivalent to $P_t = (1+\pi_{t-1})P_{t-1}$ which has been used in Christiano *et al.* (2001).

[9] See equation (A2) in the appendix for details regarding this result.

Here we will take a look at the aggregate magnitudes. All the variables are identical among households except for those that depend on the specific price setting conditions of the household: the selling price, output, and the demands for labor and capital.

Let $\overline{y}_t(j)$ denote the average output produced in aggregate output units by the households who last changed their price optimally j periods ago. In addition, let $\overline{n}_t^d(j)$ and $\overline{k}_t(j)$ denote their average quantities of labor and capital demanded. These average figures need to be calculated when taking into consideration the various price adjustment schemes that may be applied from period $t-j$ to period t.

Substituting the government budget constraint (14) in the household budget constraint, and adding up all the household budget constraints with their respective densities, we get the overall resources constraint

$$\sum_{j=0}^{\infty}\left[(1-\eta)\eta^j\overline{y}_t(j)\right] = c_t + \sum_{j=0}^{\infty}\left[(1-\eta)\eta^j\left(\overline{k}_t(j)-(1-\delta)\overline{k}_{t-1}(j)\right)\right] + w_t\left[\sum_{j=0}^{\infty}\left[(1-\eta)\eta^j\overline{n}_t^d(j)\right]-n_t^s\right]. \tag{15}$$

We assume perfect competition in the labor market. Therefore, the real wage is the market-clearing wage. Since labor supply is identical among households there will be equilibrium in the labor market when the average labor demand equals the amount of labor supplied by the representative household:

$$\sum_{j=0}^{\infty}(1-\eta)\eta^j\overline{n}_t^d(j) = n_t^s. \tag{16}$$

Taking both (15) and (16) into consideration, the overall resources constraint is

$$\overline{y}_t = c_t + \overline{k}_t - (1-\delta)\overline{k}_{t-1}, \tag{17}$$

where $\overline{y}_t = \sum_{j=0}^{\infty}\left[(1-\eta)\eta^j\overline{y}_t(j)\right]$ and $\overline{k}_t-(1-\delta)\overline{k}_{t-1} = \sum_{j=0}^{\infty}\left[(1-\eta)\eta^j\left(\overline{k}_t(j)-(1-\delta)\overline{k}_{t-1}(j)\right)\right]$.

Finally, we intend to express $\overline{y}_t$ in steady state in terms of both average labor and capital entering the production function. As shown in the appendix, there is a steady-state relationship between $\overline{y}$ and $f(\overline{n},\overline{k})$

$$\overline{y} = \phi f(\overline{n},\overline{k})$$

where $\phi = \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}\right]^{\theta/(\theta-1)}\left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]}\right]^{-1}$, and variables without time subscripts denote steady-state figures. The link factor ϕ depends on the steady state rate of inflation π, the Dixit-Stiglitz elasticity θ, and the price stickiness parameters η and χ.[10] Hence, the steady-state overall resources constraint can be formulated as follows

$$\phi f(\overline{n},\overline{k}) = c + \delta\overline{k}. \tag{17'}$$

[10] Note that the value of ϕ is equal to 1.0, and therefore $\overline{y} = f(\overline{n},\overline{k})$, when either $\eta = 0.0$ (fully flexible prices), $\chi = 1.0$ (full price indexation), or when $\pi = 0.0$ (constant prices in steady state).

The steady state solution of the model is computed by solving the system consisting of the household first order equations in steady state, and the equations describing the economy presented above. A reduced system of twelve equations is written at the end of the appendix.

3 Non-superneutrality channels

This section is intended to provide a theoretical explanation of the process that originates long-run changes in real variables when there is a change in the monetary conditions. In this model without economic growth, the steady-state nominal money growth rate μ determines the steady-state rate of inflation π because the real money balances $m = \frac{M}{PA}$ are constant in steady state. In turn, growth rates for nominal money and prices must be equal, yielding $\mu = \pi$. Thus, we will indistinctly refer to the long-run effects of either inflation or money growth.

In this type of monopolistic competition model featuring sticky prices, there are two transmission channels from inflation to the real variables in steady state: the monetary services channel and the "capital tax" channel. Let us study them separately.

i) Monetary services channel (the Friedman channel).

A rise in steady-state inflation, π, will increase on a unit per unit basis the steady-state nominal interest rate, R. This is due to the fact that in steady state the real interest rate r is equal to the household rate of time preference, ρ, and therefore it does not vary with a new steady-state rate of inflation. As a result we have $r = \rho$ and the steady-state nominal interest rate is $R = r + \pi(1 + r) = \rho + \pi(1 + \rho) \cong \rho + \pi$.

If inflation and the nominal interest rate go up, the money demand behavior of the households will lead to less real money balances m held.[11] Moreover, the transactions-facilitating role of money gives rise to a negative first derivative $s_m < 0$ in the shopping time function. In accordance, less real money balances resulting from a more inflationary scenario will bring about more shopping time, s, spent on carrying out transactions. Therefore, if the only effect of high inflation were rising s, labor supply would shrink through the time constraint and we would find less labor entering the production function.[12]

[11] In the time-cost transactions technology model at hand, the money demand equation derived from the first order conditions says that real money balances depend positively upon the current level of consumption and the real wage, and negatively upon the nominal interest rate (see the appendix for the explicit money demand expression).

[12] Note that less real money balances also drive up marginal transaction costs (as assumed $s_{cm} < 0$). In turn, consumption becomes more costly and households also shift part of their labor supply to leisure. Nonetheless, this effect seems to be quantitatively fairly negligible.

Assuming complementarity between labor and capital in the production technology $f_{nk} > 0$, a fall in labor will reduce marginal productivity of capital. In turn, the amount of capital demanded will also fall. With both labor and capital falling, output will also fall. Superneutrality does not hold and there is a negative long-run relationship between output and inflation.

We could refer to this channel as the Friedman rule channel because it implies an optimal rate of inflation that drives nominal interest rates down to 0%, as pointed out by Friedman (1969). If the nominal interest rate is at 0% the opportunity cost of holding money is null and the amount of real money balances held is maximum. On the contrary, any positive nominal interest rate gives rise to some loss of monetary services that will bring about more transaction costs. Then, some resources will be withdrawn from the productive processes to be used in carrying out transactions. As a result, there will be a negative impact on output that will originate some welfare cost of inflation. The Friedman rule says that prices must be decreasing at a deflation rate π^* approximately equal to the real interest rate: $\pi^* = -r/(1+r)$. That will yield the optimal 0% nominal interest rate which guarantees maximum monetary services held at the exchanges.

ii) The "capital tax" channel in monopolistic competition with sticky prices.

Capital-labor allocation is optimal when the ratio of marginal productivity to its factor price is the same for capital as for labor. In steady-state magnitudes, we have

$$\frac{f_n}{w} = \frac{f_k}{(\rho+\delta)/(1+\rho)}, \tag{18}$$

where we used $r = \rho$. Let us introduce the mark-up in real terms denoted as $\psi = \frac{f_n}{w} = \frac{f_k}{(\rho+\delta)/(1+\rho)}$. The real mark-up is the inverse of the real marginal cost.[13] Let us relate ψ to the steady state capital k. The Cobb-Douglas technology inserted on the right hand side of (18) determines that k is equal to

$$k = n \left[\frac{\alpha(1+\rho)}{\psi(\rho+\delta)} \right]^{1/(1-\alpha)}, \tag{19}$$

where it can be appreciated that a higher ψ leads to a lower k. This creates a distortion that shapes capital accumulation and leads to the well-known efficiency loss with respect to perfect competition. In perfect competition models, ψ is always equal to 1. However, if the economy is in monopolistic competition, the mark-up is greater than one ($\psi > 1$). For this reason, it is said that the presence of monopolistic competition gives rise to a tax on capital accumulation interpreted as the higher opportunity cost in terms of current production return.

[13] Taking into account the Cobb-Douglas production technology at hand the real marginal cost can also be expressed as a function of the factor prices:
$\psi^{-1} = \left(\frac{w}{1-\alpha}\right)^{1-\alpha} \left(\frac{\rho+\delta}{\alpha(1+\rho)}\right)^{\alpha}$.

In the appendix, we obtained the value of ψ

$$\psi = \frac{\theta}{\theta-1}\frac{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]}\left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}\right]^{1/(1-\theta)} \quad (20)$$

that is fully determined by the steady state rate of inflation π, and the parameters β, θ, η, and χ. Consequently, there is a steady-state link between π and ψ.

Considering (19) and (20), we can see that the way ψ responds to changes in π will be crucial in determining the steady-state effects of inflation on capital. Moreover, a brief inspection of (20) already tells us that the price setting conditions will play a significant role in explaining this impact through the parameters η and χ. We will calculate the effects of changes in steady-state inflation under several price setting variants in section 5. Before proceeding in that direction, we need to calibrate the remaining parameters of the model.

4 Calibration

The model is meant to give quarterly observations. In the baseline calibration both nominal money and prices grow 1% per quarter in steady state ($\mu = \pi = 0.01$), 4% per year. The rate of time preference is set at 0.5% per quarter ($\rho = 0.005$), 2% per year, which implies $\beta = 0.995$. The steady-state nominal interest rate is 1.5% per quarter ($R = 0.015$), 6% per year obtained as the sum of the real interest rate and the rate of inflation.

The instantaneous utility function is given by the constant relative risk aversion (CRRA) specification:

$$U(c_t, l_t) = \frac{c_t^{1-\sigma}}{1-\sigma} + \Upsilon\frac{l_t^{1-\gamma}}{1-\gamma}$$
$$with\ \sigma, \gamma, \Upsilon > 0.$$

The consumption risk aversion coefficient σ is set at $\sigma = 4$ so as to imply an elasticity of intertemporal substitution of consumption equal to 0.25. As for the leisure risk aversion coefficient, we took $\gamma = 8$ which led to a rather low labor supply elasticity to the real wage (+0.25) consistent with the microeconomic empirical evidence reported by Pencavel (1986). The leisure scale parameter in the utility function Υ is set to imply that one third of the total time is spent working in the baseline calibration.

The existing transactions technology is described by a functional form very similar to that described in Den Haan (1990)

$$s(c_t, m_t) = \left\{ \begin{array}{ll} 0 & if\ c_t = 0 \\ a_0 + c_t a_1 \left[\frac{c_t}{m_t}\right]^{a_2/(1-a_2)} + a_3 m_t, & if\ c_t > 0 \end{array} \right\},$$

with $a_0, a_1, a_3 \geq 0$, and $0 \leq a_2 \leq 1$. The constant term a_0 was calibrated by considering shopping time, s, to be 2% of the total time in steady state. The value a_1 implies a baseline steady-state ratio m/c equal to 1.5 as roughly observed in modern economies, whereas $a_2 = 0.75$ implies a -0.25 nominal interest rate elasticity in the money demand function.

The specification selected for the transactions technology implies the existence of a satiation point in real money balances, due to the presence of linear storage costs expressed as $a_3 m_t$. Then, if the nominal interest rate were zero (Friedman rule), households would not demand infinite real money balances. We decided to calibrate the storage cost coefficient, a_3, in order to imply that monetary services satiation occurs when the amount of real money balances held is equal to 3 times the quarterly consumption level in steady state (that is, precisely, twice what is held in the baseline steady-state solution).

In the Cobb-Douglas production technology the capital share parameter is $\alpha = 0.36$. The depreciation rate for capital δ will be 2.5% per quarter ($\delta = 0.025$). In addition, we set the Dixit-Stiglitz parameter at $\theta = 10$, implying that the elasticity of substitution between differentiated goods is equal to 10 and the steady-state mark-up of prices over marginal costs, when prices are fully flexible, is 11.1%.

As for the price setting calibration, there will be several variants analyzed in the next section ranging from the fully flexible price case to the sticky price case with no price adjustment. We will now focus on the implications of these different price setting specifications.

5 The steady-state analysis of inflation under several price setting variants

The alternatives initially proposed are four:

i) Fully flexible prices ($\eta = 0.0$). All the selling prices can be adjusted optimally at each period.

ii) Sticky prices ($0.0 < \eta < 1.0$) with full price indexation ($\chi = 1.0$). There is a fraction η of households who cannot set the price optimally at each period. All of them will adjust the price by applying the rule $P_t = (1 + \pi)P_{t-1}$.

iii) Sticky prices ($0.0 < \eta < 1.0$) with partial price indexation ($0.0 < \chi < 1.0$). There is a fraction η of households who cannot set the price optimally at each period. Some of them, a fraction $\eta\chi$, will adjust the price by applying the rule $P_t = (1+\pi)P_{t-1}$. The remaining households, the fraction $\eta(1 - \chi)$, will maintain the price unchanged $P_t = P_{t-1}$.

iv) Sticky prices ($0.0 < \eta < 1.0$) with no price adjustment ($\chi = 0.0$). There is a fraction η of households who cannot set the price optimally at each period. All of them will keep the price unchanged $P_t = P_{t-1}$.

Regarding the long-run analysis at hand, the four price setting cases presented correspond to only three different models because cases i) and ii) have the same steady-state properties. If all the non-optimal prices are fully indexed, all the prices of the economy will be growing at the steady-state rate of inflation. In turn, the two economies behave identically on a steady-state basis (see the appendix for details). Hence, we refer indistinctly to both cases i) and ii) as Model 1. The sticky-price economy with partial price indexation will be Model 2, whereas the sticky-price economy with no price indexation (the original assumption in Calvo (1983)) will be Model 3.

For the sake of consistency, the parameters Υ, a_0, a_1, and a_3 will be assigned to maintain the baseline calibration assumptions. Hence, the calibration of these parameters for any of the three models implies that at the (baseline) steady-state rate of inflation of 4% per year: 1/3 of the time is devoted to work, 2% of the time is devoted to shopping, $m/c = 1.5$, and money satiation occurs when $m/c = 3.0$.

The analysis will consist of a case-by-case examination of the different steady-state implications found when altering the rate inflation. The rates will start at the Friedman-rule rate (roughly -2% per year) rising to 10% per year.[14] Figures 1-3 and Tables 1-3 display the results for Models 1-3. The variables reported are: real money balances (m), shopping time (s), the mark-up (ψ), the real wage (w), average capital (k), average labor (n), consumption (c), leisure (l), average output (y), and the welfare cost of inflation (welfare cost). The welfare cost of inflation was calculated as the percentage of output required to gain sufficient utility to render the household indifferent with respect to the optimal inflation case.

Model 1. Fully flexible prices or sticky prices with full price indexation.

This "capital tax" channel vanishes when prices are either fully flexible to adjust optimally ($\eta = 0.0$) or sticky with all the non-optimal prices following the indexation rule ($0.0 < \eta < 1.0$ and $\chi = 1.0$). In both cases, expression (20) yields $\psi = \frac{\theta}{\theta - 1}$ and the inflation-markup link disappears. Figure 1 shows this result as the horizontal line in the plot of the real mark-up ψ. When inflation changes, there is no change in the tax on capital accumulation coming from the monopolistic competition setup.

Hence, the only way of explaining departures from superneutrality is through the Friedman-type channel. The two most important effects of any increase in steady state inflation are the decline in real money balances and the increase in the transaction costs (shopping time) due to

[14] The Friedman-rule rate of inflation in annualized percentage terms is $\pi^* = 400 * \left(\frac{-\rho}{1+\rho}\right)$. Inserting the calibrated figure $\rho = 0.005$, we obtain $\pi^* = -1.99\%$.

the loss of monetary services. Examples shown in Table 1 show that real money falls by 50% when inflation rises from -2% per year to 4% per year and by close to 60% when inflation reaches 10% per year. Shopping time, meanwhile, goes up by 12.9% when annual inflation moves up from -2% to 4% and by nearly 25% when inflation reaches10%.

Figure 1. Model 1. Flexible prices or sticky prices with full price indexation. Effects of increasing annual inflation in steady state.

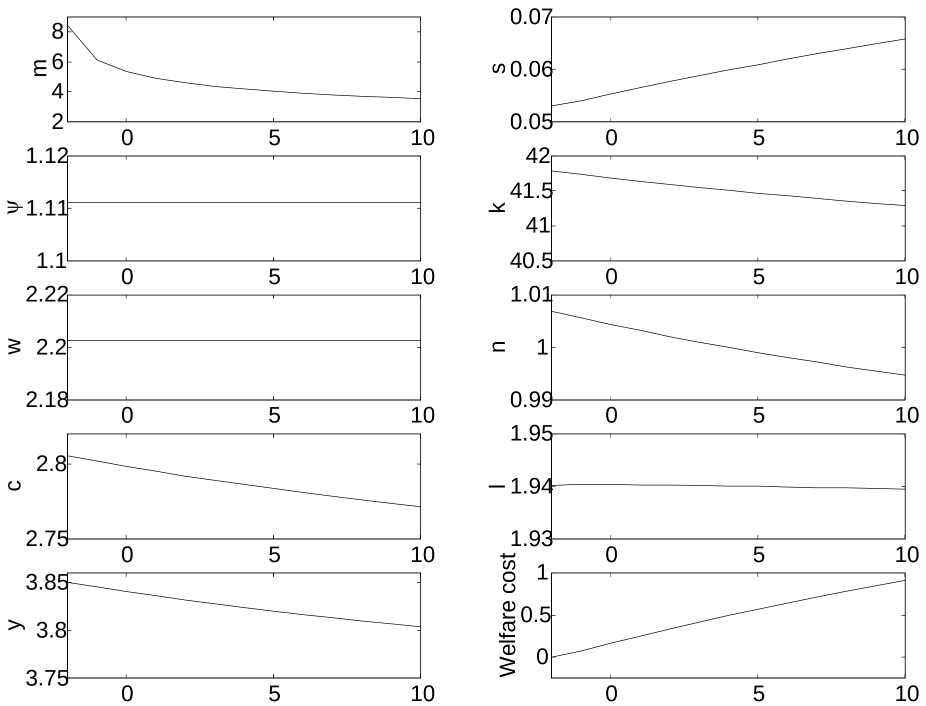


Table 1. Model 1. Flexible prices or sticky prices with full price indexation. Effectsof increasing annual inflation in steady state from Friedman rule (-1.99%).

	Percent changes in relevant variables									Welfare cost
π	m	s	ψ	k	w	n	c	l	y	
0%	-36.41	4.18	0	-0.25	0	-0.25	-0.25	0.01	-0.25	0.16
4%	-50.35	12.92	0	-0.68	0	-0.68	-0.68	0	-0.68	0.50
10%	-57.99	24.02	0	-1.20	0	-1.20	-1.20	-0.03	-1.20	0.91

This increase in shopping time s will bring about a fall in average labor n. This fall in labor will drive capital down as implied by (19). Average output will also fall as a consequence of the decline in both labor and capital. These are only minor reductions in average labor, average capital, average output, and consumption (see Figure 1). In fact, they all report the same decrease in percentage units. Two examples reported in Table 1 show that when annual inflation moves up from the Friedman rule figure to 4%, all these variables drop by 0.68%, and if steady-state inflation reaches 10% per year, they all fall by 1.20%.

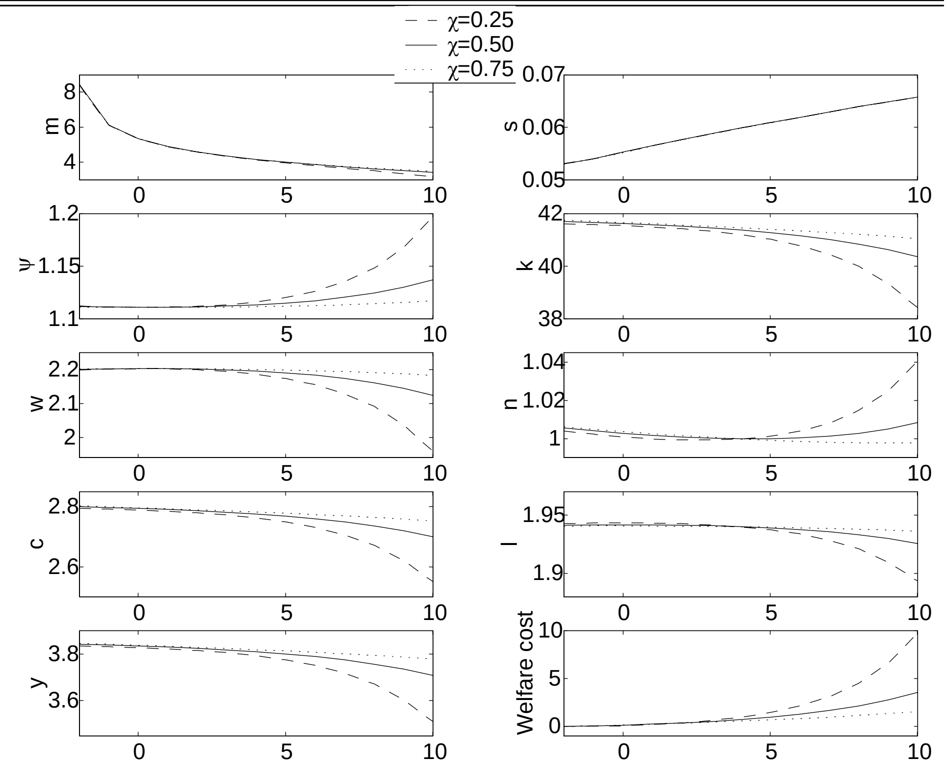
Finally, the estimates of the welfare cost of inflation are also quite low: when prices are constant (0% inflation) the welfare cost is 0.16% of output, a 4% annual inflation produces a welfare cost of 0.50% of output, and a 10% inflation has a welfare cost equal to 0.91%. The optimal rate of inflation is the Friedman rule rate (-1.99% per year).

Model 2. Sticky prices with partial price indexation.

In Figure 2 and Table 2 we display and report the steady state effects of inflation in a economy with sticky prices ($\eta = 0.75$), and partial price indexation. Prices are set optimally only with a probability equal to $1 - \eta = 0.25$. This means that on average the selling price will be adjusted optimally only once per year. However, there exists another form of price adjustment through the indexation rule. We examined the results at three different levels of price indexation according to their probabilities: high ($\chi = 0.75$), medium ($\chi = 0.50$), and low ($\chi = 0.25$).

The strongest impact of increasing inflation is observed in real money balances and shopping time very close to what occurs in the flexible-price economy: there is a significant fall in m and a severe increase in transaction costs s. This result is robust to any price indexation level.

Figure 2. Model 2. Sticky prices with partial price indexation. Effects of increasing annual inflation in steady state.



However the remaining variables show different patterns depending on the value of χ. In the economy with a high level of price indexation ($\chi = 0.75$), the steady-state effects of inflation are quantitatively much weaker than in the economy with low price indexation ($\chi = 0.25$). Observation of Figure 2 reveals that the real mark-up, ψ, increases with higher inflation. The absence of full price indexation ($0.0 \leq \chi < 1.0$) in a sticky-price economy ($0.0 < \eta < 1.0$) gives rise to a steady-state link between inflation, π, and the real mark-up, ψ, as shown in (20). Consequently, the capital tax channel matters in the steady-state analysis of inflation. This response is much stronger when there is little price indexation ($\chi = 0.25$). Put differently, the capital tax channel is more influential with a low level of price indexation, and capital, output and consumption fall very heavily. As Table 2 reports, when steady-state annual inflation moves from -2% to 10%, capital, output and consumption fall by around 8% in the low-indexed economy ($\chi = 0.25$), whereas they decrease by less than 2% in the high-indexed economy ($\chi = 0.75$).

Table 2. Model 2. Sticky prices with partial price indexation.
Effectsof increasing annual inflation in steady state from Friedman rule (-1.99%).

$\chi = 0.75$										
	Percent changes in relevant variables									Welfare cost
π	m	s	ψ	k	w	n	c	l	y	
0%	-36.42	4.18	-0.02	-0.22	0.03	-0.25	-0.22	0.01	-0.22	0.15
4%	-50.41	12.92	0.04	-0.69	-0.06	-0.64	-0.73	-0.02	-0.72	0.56
10%	-58.34	23.99	0.54	-1.67	-0.83	-0.84	-1.77	-0.22	-1.75	1.54
$\chi = 0.50$										
	Percent changes in relevant variables									Welfare cost
π	m	s	ψ	k	w	n	c	l	y	
0%	-36.35	4.17	-0.05	-0.18	0.08	-0.27	-0.20	0.03	-0.20	0.12
4%	-50.46	12.90	0.15	-0.79	-0.23	-0.56	-0.86	-0.06	-0.84	0.70
10%	-59.34	23.95	2.31	-3.22	-3.50	0.29	-3.57	-0.80	-3.47	3.54
$\chi = 0.25$										
	Percent changes in relevant variables									Welfare cost
π	m	s	ψ	k	w	n	c	l	y	
0%	-36.25	4.16	-0.09	-0.15	0.15	-0.30	-0.18	0.04	-0.17	0.08
4%	-50.54	12.87	0.37	-0.97	-0.57	-0.40	-1.10	-0.15	-1.06	0.96
10%	-62.19	23.80	7.67	-7.66	-10.90	3.64	-8.72	-2.53	-8.43	9.77

It is also interesting to notice that the effect of inflation on labor differs in direction depending on the level of indexation χ. Since the impact on consumption is much stronger with low indexation we observe a positive response of labor at high rates of inflation. Labor supply expands far enough to outweigh the contraction of labor demand. Thus, the labor market clears with a greater quantity of labor and a fall in the real wage (see Figure 2, boxes w and n). The increase in labor is more noticeable when the economy features little price indexation, $\chi = 0.25$.

Regarding the welfare cost of inflation, the two arguments of the utility function, consumption and leisure, describe larger falls in response to higher inflation when the economy exhibits a low level of price indexation, especially within the high-inflation range. In turn, the welfare cost is also larger (see the welfare cost box in Figure 2). For example, a 10% rate of inflation has a welfare cost equal to 1.54% of output when $\chi = 0.75$ and equal to 9.77% of output when $\chi = 0.25$.

With partial price indexation the optimal rate of inflation is no longer at the Friedman rule. The reason behind this result is that initial increments of inflation from the Friedman rule produce slight falls in the real mark-up. In other words, there exists a u-shape response of the real mark-up to inflation within the negative rates range. This result is reported in Table 2. What we have there is a negative change in ψ as inflation moves from -2% to 0%. This drop is more significant for a lower level of price indexation. A decrease in the capital tax is an incentive for capital accumulation. Unfortunately we cannot observe this in Figure 2 because the figures are very low compared to the positive impact reported at positive rates of inflation. The optimal rate of inflation was found to be -1.71% when $\chi = 0.25$, -1.90% when $\chi = 0.50$, and -1.98% when $\chi = 0.75$. In all three cases the optimal rate is higher than the Friedman rule rate.

Model 3. Sticky prices with no price indexation (Calvo economy).

An economy without the possibility of price indexation is now analyzed. The absence of any price adjustment when prices cannot be set optimally was the assumption taken in the seminal paper by Calvo (1983). Thus, we denominate this case as the Calvo economy. Taking $\eta = 0.75$ and $\chi = 0.0$, a fraction $1 - \eta = 0.25$ of the prices are set optimally whereas the rest of the prices, the fraction $\eta = 0.75$, remain unchanged.

Figure 3 and Table 3 show that two major effects of higher inflation are the fall in real money balances and the increase in transaction costs as previously observed in both Model 1 and Model 2. Nevertheless, it is also reported that other variables respond to higher inflation much more aggressively than in the previous models. In particular, capital, output and consumption drop dramatically when inflation rates rise to 10% per year. The origin of these sharp falls is the strong response of the real mark-up to increasing rates of inflation. Some numbers illustrate this result in Table 3. When inflation rises from -2% to 10% in steady state, the real mark-up ψ also rises by more than 30%. The stock of capital is dramatically affected as it falls by nearly 23%. Output and consumption also report very severe drops. They both fall by more than 25% when inflation moves from -2% to 10%. Such a wide departure from superneutrality seems very unrealistic.

The explanation of this strong negative effect is rather intuitive. If there is no possibility for price indexation and the rate of inflation reaches moderately high figures, producers become more aggressive when adjusting the price optimally. They know that they might face a long period without being able to change the price. Their optimal price is set substantially higher than the marginal cost. This implies a very high real mark-up. In turn, the capital tax channel exerts a very harmful effect on capital accumulation. Capital, output, and consumption fall dramatically.

Figure 3. Model 3. Sticky prices with no price indexation (Calvo economy). Effects of increasing annual inflation in steady state.

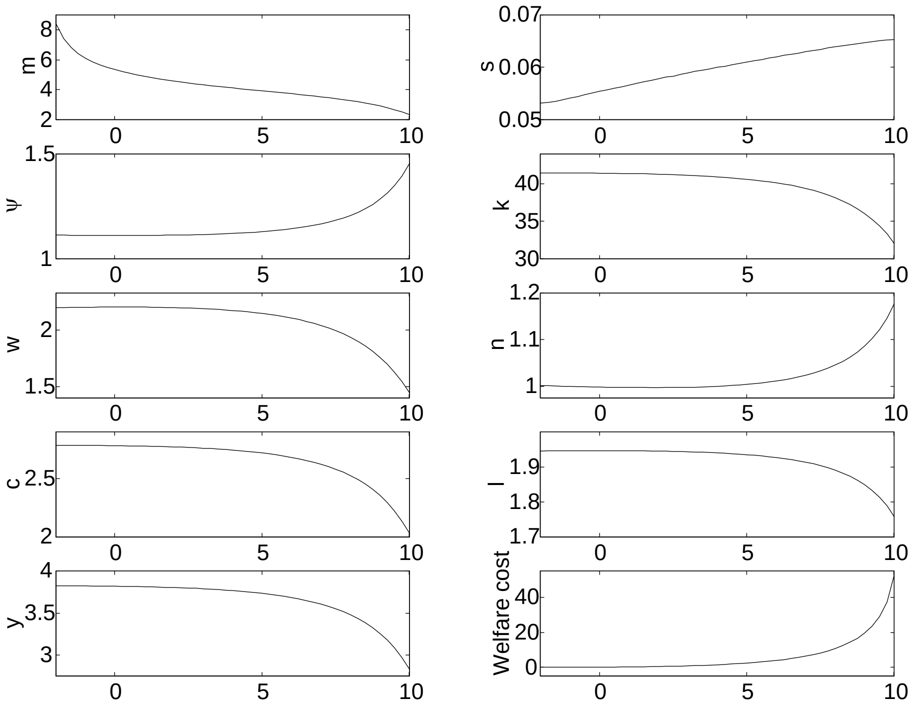


Table 3. Model 3. Sticky prices with no price indexation (Calvo economy). Effectsof increasing annual inflation in steady state from Friedman rule (-1.99%).

	Percent changes in relevant variables									Welfare cost
π	m	s	ψ	k	w	n	c	l	y	
0%	-36.14	4.14	-0.14	-0.09	0.22	-0.31	-0.12	0.05	-0.11	0.05
4%	-50.75	12.79	0.74	-1.29	-1.15	-0.14	-1.49	-0.28	-1.43	1.42
10%	-71.92	22.88	30.65	-22.67	-34.14	17.41	-27.10	-9.59	-25.90	52.61

When inflation rises labor reacts in the opposite direction to capital. There is a significant increase in labor when inflation approaches 10% per year. This result was already discussed in Model 2 for the case with low indexation. The Calvo economy can be viewed as the extreme case with no indexation. The significant decrease in consumption shifts the labor supply curve to the right, i.e., households wish to work more and average labor increases.

Meanwhile, figures for the welfare cost of inflation are also very high as both consumption and leisure fall in response to higher rates of inflation. Annual inflation of 4% has a welfare cost equal to 1.42% of output. There is a very rapid increase in the welfare cost for higher rates. A 10% rate of inflation per year produces a welfare cost of 52.6% of output which means more than one half of the total output produced per year! This is indeed very unrealistic and would push producers to use some price indexation scheme as the one featured by Model 2.

Finally, the optimal rate of inflation is at -1.32% per year, higher than Friedman rule. As discussed in Model 2, the initial negative impact on the real mark-up that comes about as a result of increasing π from the Friedman-rule rate creates positive welfare effects and the optimal rule is no longer at the Friedman rule.

6 Conclusions

There are two different channels of deviation from superneutrality in an optimizing monetary model with monopolistic competition and sticky prices: the monetary services channel and the "capital tax" channel. The first of these is based on the money demand behavior that leads to less real money held when inflation rises. A decrease in monetary services brings about the need to use some resources to cover transaction costs. This mechanism corresponds to the classic Friedman rule analysis of inflation. As for the "capital tax" channel, it can be described by saying that higher inflation affects the mark-up of prices over marginal costs, which acts as a tax on capital accumulation decisions.

The price setting characteristics of the economy have significant influence in the steady-state analysis of inflation. Hence, the "capital tax" is only affected by inflation if prices are sticky and at least a fraction of the non-optimal prices are not indexed. Therefore, when prices are flexible or there are sticky prices with full price indexation, the monetary services channel is the only mechanism that will account for superneutrality deviations. In turn, any steady-state rise in inflation leads to quantitatively minor reductions in capital, labor, and output. In this case, the Friedman-rule rate of inflation (which leads to a 0% nominal interest rate) becomes the optimal one on a steady state basis.

By contrast, if prices are sticky and there is not full price indexation, the "capital tax" channel becomes the driving force governing the steady-state effects of inflation, since its implications are very influential on capital, labor, output, and consumption. In addition, the optimal rate of inflation is no longer at the Friedman rule. This paper has shown that the level of price indexation in the economy becomes crucial in determining the size of the steady-state effects of inflation.

Thus, an economy with a low level of price indexation is more severely affected by a rise in the steady state rate of inflation than an economy where most of the non-optimal prices are indexed. For example, if only one fourth of the non-optimal prices are indexed a change in inflation from -2% per year to 10% per year causes output to fall by 8.43%. If three fourths of the non-optimal prices are being indexed the fall is only by 1.75%.

We also studied the long-run effects of inflation in an economy where all the non-optimal prices remain unchanged, i.e., there is no price indexation at all. This extreme case corresponds to the original Calvo-type economy. We detected unrealistic features in the steady-state responses of this model to increases in the rate of inflation. Both capital and output reported excessively high increases, of around 25% when steady-state inflation moves from -2% to 10% per year. As a result, estimates of the welfare cost of inflation grow very rapidly with higher inflation (they reach a level of more than 50% of output at a 10% annual rate of inflation).

Our results support the primary goal of price stability in the design of a long-run strategy for monetary policy. Low-inflation economies (from the Friedman rule to 4% per year) report low estimates of the welfare cost of inflation. This result is robust to any pricing specification.

APPENDIX.

• The Dixit-Stiglitz aggregate price level P_t^A with sticky prices and price indexation.

Both the Calvo-type price stickiness and the possibility of price adjustment imply that the Dixit-Stiglitz aggregate price level P_t^A is

$$\begin{aligned} P_t^A = & [(1-\eta)[P_t(0)]^{1-\theta} + (1-\eta)\eta\chi[(1+\pi)P_{t-1}(0)]^{1-\theta} + (1-\eta)\eta(1-\chi)[P_{t-1}(0)]^{1-\theta} + \\ & (1-\eta)\eta^2\chi^2\left[(1+\pi)^2 P_{t-2}(0)\right]^{1-\theta} + 2(1-\eta)\eta^2\chi(1-\chi)[(1+\pi)P_{t-2}(0)]^{1-\theta} + \\ & (1-\eta)\eta^2(1-\chi)^2[P_{t-2}(0)]^{1-\theta} + ...]^{1/(1-\theta)}, \end{aligned}$$

where $P_{t-j}(0)$ is the optimal price in period $t-j$. The previous expression can be expressed more briefly as

$$P_t^A = \left[(1-\eta)[P_t(0)]^{1-\theta} + \eta\left[(1-\chi) + \chi(1+\pi)^{1-\theta}\right]\left[P_{t-1}^A\right]^{1-\theta}\right]^{1/(1-\theta)}. \tag{A1}$$

Particular cases worth noting are

$$\begin{aligned} \eta &= 0.0 \text{ (flexible prices)} \rightarrow P_t^A = P_t(0) \\ \eta &> 0,\ \chi = 1.0 \text{ (full indexation)} \rightarrow P_t^A = \left[(1-\eta)[P_t(0)]^{1-\theta} + \eta\left[(1+\pi)P_{t-1}^A\right]^{1-\theta}\right]^{1/(1-\theta)} \\ \eta &> 0,\ \chi = 0.0 \text{ (Calvo economy)} \rightarrow P_t^A = \left[(1-\eta)[P_t(0)]^{1-\theta} + \eta\left[P_{t-1}^A\right]^{1-\theta}\right]^{1/(1-\theta)} \end{aligned}$$

• The steady-state relationship between the optimal price $P(0)$ and the Dixit-Stiglitz aggregate price level P^A.

Equation (A1) in steady state implies the following relationship between the price optimally adjusted in the current period $P(0)$ and the aggregate price level P^A

$$\frac{P(0)}{P^A} = \left[\frac{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1} + \chi\right]}{1-\eta}\right]^{1/(1-\theta)}. \tag{A2}$$

Particular cases worth noting are

$$\begin{aligned} \eta &= 0.0 \text{ (flexible prices)} \rightarrow P(0) = P^A \\ \eta &> 0,\ \chi = 1.0 \text{ (full indexation)} \rightarrow P(0) = P^A \\ \eta &> 0,\ \chi = 0.0 \text{ (Calvo economy)} \rightarrow P(0) = P^A\left[\frac{1-\eta(1+\pi)^{\theta-1}}{1-\eta}\right]^{1/(1-\theta)} \end{aligned}$$

• The steady-state relationship between average output $\overline{y}$ and $f(\overline{n}, \overline{k})$.

The Calvo price setting distribution at hand gives rise to the following definition of average output in steady state $\overline{y}$

$$\overline{y} = \sum_{j=0}^{\infty}\left[(1-\eta)\eta^j\overline{y}(j)\right], \tag{A3}$$

where $\overline{y}(j)$ is the average output produced by the fraction of producers who last set their price optimally j periods ago. The value of $\overline{y}(j)$ is expressed in aggregate output units. The amount produced by each household will be depending on the specific selling price (that might have been indexed or not). Taking this into consideration, and the respective Dixit-Stiglitz demand functions for each set price, the steady state value of $\overline{y}(j)$ is

$$\overline{y}(j) = \left[\sum_{k=0}^{j} \frac{j!}{(j-k)!k!} \chi^{j-k} (1-\chi)^{k} (1+\pi)^{(1-\theta)(j-k)} \right] \left(\frac{P_{-j}(0)}{P^{A}} \right)^{1-\theta} y^{A},$$

where $P_{-j}(0)$ is the steady-state optimal price set j periods ago. The previous expression is equivalent to

$$\overline{y}(j) = \left[1 + ((1+\pi)^{1-\theta} - 1)\chi \right]^{j} \left(\frac{P_{-j}(0)}{P^{A}} \right)^{1-\theta} y^{A}. \tag{A4}$$

The ratio $P_{-j}(0)/P^{A}$ can be decomposed in

$$\frac{P_{-j}(0)}{P^{A}} = \frac{P_{-j}(0)}{P(0)} \frac{P(0)}{P^{A}}. \tag{A5}$$

Since $P(0)/P^{A}$ is constant (see (A2)), the optimal selling price $P(0)$ must grow at the same rate as the aggregate price level P^{A}. In turn, the steady-state condition that drives the change in optimal prices for the last j periods is

$$P(0) = (1+\pi)^{j} P_{-j}(0). \tag{A6}$$

Inserting this result into the price decomposition (A5) and substituting it in equation (A4) yields, after some algebra,

$$\overline{y}(j) = \left[(1-\chi)(1+\pi)^{\theta-1} + \chi \right]^{j} \left(\frac{P(0)}{P^{A}} \right)^{1-\theta} y^{A}. \tag{A7}$$

The value of $\overline{y}(j)$ given by (A7) is introduced into (A3) in order to obtain

$$\overline{y} = \sum_{j=0}^{\infty} (1-\eta)\eta^{j} \left[(1-\chi)(1+\pi)^{\theta-1} + \chi \right]^{j} \frac{P(0)}{P^{A}} \left(\frac{P(0)}{P^{A}} \right)^{-\theta} y^{A}, \tag{A8}$$

where the introduction of $y(0)$, the amount of output produced at $P(0)$, implies

$$\overline{y} = \sum_{j=0}^{\infty} (1-\eta)\eta^{j} \left[(1-\chi)(1+\pi)^{\theta-1} + \chi \right]^{j} \frac{P(0)}{P^{A}} y(0).$$

By computing the sum over j, we obtain

$$\overline{y} = \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1} + \chi\right]} \right] \frac{P(0)}{P^{A}} y(0),$$

Now $P(0)/P^{A}$ is substituted by its steady state value obtained in (A2) so as to reach

$$\overline{y} = \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1} + \chi\right]} \right] \left[\frac{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1} + \chi\right]}{1-\eta} \right]^{1/(1-\theta)} y(0),$$

which implies the following steady-state expression relating $\overline{y}$ to $y(0)$

$$\overline{y} = \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]} \right]^{\theta/(\theta-1)} y(0). \tag{A9}$$

So far, we have found a steady state relationship between $\overline{y}$ and $y(0)$. We will now proceed by deriving the analogous steady state expression relating $f(\overline{n},\overline{k})$ to $y(0)$ in order to induce a steady-state relationship between $\overline{y}$ and $f(\overline{n},\overline{k})$. The value given by $f(\overline{n},\overline{k})$ is the amount of output produced when plugging the steady-state average labor $\overline{n}$, and the steady-state average capital $\overline{k}$ into the Cobb-Douglas production function

$$f(\overline{n},\overline{k}) = [\overline{n}]^{1-\alpha} \left[\overline{k}\right]^{\alpha}. \tag{A10}$$

Under the Calvo setup, the steady-state average labor and capital are

$$\begin{aligned} \overline{n} &= \textstyle\sum_{j=0}^{\infty}(1-\eta)\eta^{j}\overline{n}^{d}(j), \\ \overline{k} &= \textstyle\sum_{j=0}^{\infty}(1-\eta)\eta^{j}\overline{k}(j), \end{aligned} \tag{A11}$$

where $\overline{n}^{d}(j)$ and $\overline{k}(j)$ are the steady-state average labor and capital demanded by the fraction of producers who were last able to set the price optimally j periods ago. Taking the price indexation probabilities into consideration, the respective Dixit-Stiglitz demand functions for each price set, and the constant returns to scale production technology, $\overline{n}^{d}(j)$ and $\overline{k}(j)$ are in steady state

$$\begin{aligned} \overline{n}^{d}(j) &= \left[\textstyle\sum_{k=0}^{j} \frac{j!}{(j-k)!k!}\chi^{j-k}(1-\chi)^{k}(1+\pi)^{-\theta(j-k)}\right] n^{d}(j), \\ \overline{k}(j) &= \left[\textstyle\sum_{k=0}^{j} \frac{j!}{(j-k)!k!}\chi^{j-k}(1-\chi)^{k}(1+\pi)^{-\theta(j-k)}\right] k(j), \end{aligned} \tag{A12}$$

where $n^{d}(j)$ and $k(j)$ are the steady-state amounts demanded by the fraction of households who set their price optimally j periods ago and have maintained it unchanged until the current period. Expression (A12) is equivalent to

$$\begin{aligned} \overline{n}^{d}(j) &= \left[1+((1+\pi)^{-\theta}-1)\chi\right]^{j} n^{d}(j), \\ \overline{k}(j) &= \left[1+((1+\pi)^{-\theta}-1)\chi\right]^{j} k(j). \end{aligned} \tag{A13}$$

Now our intention is to write $\overline{n}^{d}(j)$ and $\overline{k}(j)$ as a function of $n^{d}(0)$ and $k(0)$, the factor demands when the price is set optimally for the current period. Since the production technology available exhibits constant returns to scale there exists a steady-state link between the factor demands at prices $P_{-j}(0)$ and $P(0)$

$$\begin{aligned} n^{d}(j) &= \left(\tfrac{P_{-j}(0)}{P(0)}\right)^{-\theta} n^{d}(0), \\ k(j) &= \left(\tfrac{P_{-j}(0)}{P(0)}\right)^{-\theta} k(0). \end{aligned}$$

Recalling (A6) yields

$$\begin{aligned} n^{d}(j) &= (1+\pi)^{j\theta}n^{d}(0), \\ k(j) &= (1+\pi)^{j\theta}k(0). \end{aligned} \tag{A14}$$

When substituting (A14) in (A13) after some algebra we get

$$\begin{aligned} \overline{n}^d(j) &= \left[(1-\chi)(1+\pi)^\theta + \chi\right]^j n^d(0), \\ \overline{k}(j) &= \left[(1-\chi)(1+\pi)^\theta + \chi\right]^j k(0). \end{aligned} \tag{A15}$$

Now by plugging the values obtained in (A15) into (A11)

$$\begin{aligned} \overline{n} &= \textstyle\sum_{j=0}^{\infty}(1-\eta)\eta^j \left[(1-\chi)(1+\pi)^\theta + \chi\right]^j n^d(0), \\ \overline{k} &= \textstyle\sum_{j=0}^{\infty}(1-\eta)\eta^j \left[(1-\chi)(1+\pi)^\theta + \chi\right]^j k(0), \end{aligned}$$

where, after solving the sum over j, we have

$$\begin{aligned} \overline{n} &= \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^\theta + \chi\right]}\right] n^d(0), \\ \overline{k} &= \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^\theta + \chi\right]}\right] k(0). \end{aligned} \tag{A16}$$

The values of $\overline{n}$ and $\overline{k}$ implied by (A16) enter the production function (A10)

$$f(\overline{n}, \overline{k}) = \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^\theta + \chi\right]}\right] \left[n^d(0)\right]^{1-\alpha} \left[k(0)\right]^\alpha,$$

which in terms of $y(0)$ yields

$$f(\overline{n}, \overline{k}) = \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^\theta + \chi\right]}\right] y(0). \tag{A17}$$

The amount of average output $\overline{y}$ as a function of $y(0)$ was given by equation (A9). Combining (A9) with (A17) leads to the following steady-state relationship between $\overline{y}$ and $f(\overline{n}, \overline{k})$

$$\overline{y} = \frac{\left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1} + \chi\right]}\right]^{\theta/(\theta-1)}}{\left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta} + \chi\right]}\right]} f(\overline{n}, \overline{k}) \tag{A18}$$

Particular cases worth noting are

$$\begin{aligned} \eta &= 0.0 \text{ (flexible prices)} \rightarrow \overline{y} = f(\overline{n}, \overline{k}) \\ \eta &> 0,\ \chi = 1.0 \text{ (full indexation)} \rightarrow \overline{y} = f(\overline{n}, \overline{k}) \\ \eta &> 0,\ \chi = 0.0 \text{ (Calvo economy)} \rightarrow \overline{y} = \frac{\left[\frac{1-\eta}{1-\eta(1+\pi)^{\theta-1}}\right]^{\theta/(\theta-1)}}{\left[\frac{1-\eta}{1-\eta(1+\pi)^{\theta}}\right]} f(\overline{n}, \overline{k}) \end{aligned}$$

- The steady state real mark-up ψ.

Under pricing conditions à la Calvo, the selling price first order condition is in steady state

$$P(0) = \frac{\theta}{\theta-1} \frac{\sum_{j=0}^{\infty} \beta^j \eta^j \left[(1-\chi)(1+\pi)^\theta + \chi\right]^j \psi^{-1} P^A y^A}{\sum_{j=0}^{\infty} \beta^j \eta^j \left[(1-\chi)(1+\pi)^{\theta-1} + \chi\right]^j y^A}, \tag{A19}$$

where ψ^{-1} is the inverse of the real mark-up. The previous expression can be simplified to reach

$$P(0) = \frac{\theta}{\theta-1} \frac{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]} \psi^{-1} P^A. \tag{A20}$$

Solving (A20) for the steady-state mark-up ψ yields

$$\psi = \frac{\theta}{\theta-1} \frac{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]} \frac{P^A}{P(0)}. \tag{A21}$$

Finally, the steady state ratio $P^A/P(0)$ implied by (A2) is inserted in (A21) in order to obtain

$$\psi = \frac{\theta}{\theta-1} \frac{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]} \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}\right]^{1/(1-\theta)}. \tag{A22}$$

Particular cases worth noting are

$$\begin{aligned}
\eta &= 0.0 \text{ (flexible prices)} \rightarrow \psi = \tfrac{\theta}{\theta-1} \\
\eta &> 0,\ \chi = 1.0 \text{ (full indexation)} \rightarrow \psi = \tfrac{\theta}{\theta-1} \\
\eta &> 0,\ \chi = 0.0 \text{ (Calvo economy)} \rightarrow \psi = \tfrac{\theta}{\theta-1} \tfrac{1-\beta\eta(1+\pi)^{\theta-1}}{1-\beta\eta(1+\pi)^{\theta}} \left[\tfrac{1-\eta}{1-\eta(1+\pi)^{\theta-1}}\right]^{1/(1-\theta)}
\end{aligned}$$

- The steady-state solution of the model.

By taking into consideration the first order conditions of the model in steady state, the labor market equilibrium condition $\sum_{j=0}^{\infty}(1-\eta)\eta^j \overline{n}_t^d(j) = n_t^s = \overline{n}_t$, the definitions presented in the main text. and the results reached above in this appendix, we are able to compute a reduced steady-state solution of the model by solving the system of equations

$$\begin{aligned}
\pi &= \mu, \\
r &= \rho, \\
R &= r + \pi(1+r), \\
\overline{y} &= \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}\right]^{\theta/(\theta-1)} \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]}\right]^{-1} \overline{n}^{1-\alpha}\overline{k}^{\alpha}, \\
\psi &= \frac{\theta}{\theta-1} \frac{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}{1-\beta\eta\left[(1-\chi)(1+\pi)^{\theta}+\chi\right]} \left[\frac{1-\eta}{1-\eta\left[(1-\chi)(1+\pi)^{\theta-1}+\chi\right]}\right]^{1/(1-\theta)}, \\
\overline{k} &= \overline{n}\left[\frac{\alpha(1+\rho)}{\psi(\rho+\delta)}\right]^{1/(1-\alpha)}, \\
w &= (1-\alpha)\left[\frac{\overline{k}}{\overline{n}}\right]^{\alpha} \psi^{-1}, \\
c &= \overline{y} - \delta\overline{k}, \\
m &= c\left[\frac{a_1 a_2 w}{1-a_2}\left(\frac{R}{(1+R)} + a_3 w\right)^{-1}\right]^{1-a_2}, \\
\overline{n} &= T - l - s, \\
s &= a_0 + a_1 c^{1/(1-a_2)} m^{-a_2/(1-a_2)} + a_3 m, \\
l &= \left[w\frac{c^{-\sigma}}{\Upsilon\left(1 + w\frac{a_1}{1-a_2}\left[\frac{c}{m}\right]^{a_2/(1-a_2)}\right)}\right]^{-1/\gamma}.
\end{aligned}$$

The twelve-equation system provides a solution for the twelve variables π, r, R, $\overline{y}$, ψ, $\overline{k}$, w, c, m, $\overline{n}$, s, and l, given some calibrated value for the parameters ρ, σ, Υ, γ, a_0, a_1, a_2, a_3, δ, α, θ, η, χ, and μ.

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