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## Adjustment cost-driven inflation inertia

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## **Adjustment Cost-Driven Inflation Inertia**

by

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# Adjustment Cost-Driven Inflation Inertia $\diamond$

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## Abstract

This paper shows how endogeneous inflation inertia is generated by a simple modification of the quadratic adjustment cost structure faced by economic agents. We derive the pertinent inflation relationships based on purely nominal rigidities and show that they always involve additional expectation terms which are absent in a Calvo-type environment. However, the structural differences do not prevent dynamic adjustment paths and theoretical moments to be similar under both rigidity assumptions. An extensive application of nominal adjustment frictions leads to a full-scale macroeconomic framework able to replicate empirical responses to an interest rate shock.

***JEL classification:*** E31; E32; E52

***Key words:*** Inflation Dynamics; New Keynesian Phillips Curve; Business Fluctuations

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# 1 Introduction

The staggered price setting according to Calvo (1983) is the most common approach to rule out the neutrality of monetary policy. Similar to the nominal wage-contracting environment suggested by Taylor (1979), an inertial adjustment of prices emerges as a salient outcome. Equivalent conclusions are derived by assuming the existence of menu costs in nominal adjustment (Rotemberg (1982) and Hairault and Portier (1993)). However, none of these rigidity specifications is able to replicate the highly amplified inflation persistence typically observed in empirical data. Most importantly, the theoretical fit towards observed fundamentals of inflation always involves an extension of the non-neutrality at work. For instance, the Calvo version is usually modified as in Galí, Gertler, and López-Salido (2001) or in Christiano, Eichenbaum and Evans (2005) to include rule-of-thumb setters. This means that a fraction of monopolistic agents is forced to index their nominal choice variable to past nominal conditions, as they are disallowed to decide optimally. In a rather overlooked consistency, the induced endogeneity in inflation variables is due to purely nominal frictions. In contrast, inflation endogeneity under the Taylor contracting and the adjustment cost assumption typically entails (additional) real frictions. A standard procedure in the Taylor-type setting is to introduce real-valued wage contracts as done by Furher and Moore (1995), while the adjustment cost environment generally assumes additional adjustment costs in input utilization<sup>1</sup>. Concerning the latter, we rule out the apparent misperception in the literature about inflation endogeneity as a specific result of real rigidities<sup>2</sup>. In particular, we show that endogenous inflation persistence could be well traced back to purely nominal rigidities in a re-

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<sup>1</sup> See for example Lechtaler and Snower (2008) for a very simple specification of labor adjustment costs. While these are embedded in a Calvo setting, the same inflation inertia can be generated by assuming quadratic adjustment costs in the pricing decision instead.

<sup>2</sup> We concentrate on the adjustment cost specification because it is increasingly applied in the optimal policy literature due to its simplicity. Examples can be found in Faia (2008) and Schmitt-Grohé and Uribe (2004). Interesting results have been obtained by Ascari and Merkl (2009) after disinflationary policy experiments in a non-linear adjustment cost setting.

defined adjustment cost environment. However, the resulting inflation curves at the aggregate level display a higher degree of complexity in terms of expectations but lead to similar qualitative results as in the rule-of-thumb Calvo setting.

The remainder is as follows. Section 2 introduces the novel adjustment cost structure and its intertemporal implications. Section 3 embeds this formulation in microeconomic optimization problems across monopolistic agents. In section 4, the pertinent optimality conditions are aggregated and linearized in order to obtain a stylized New Keynesian macroeconomic framework. The latter is calibrated and simulated in section 5. We compare its dynamic and numerical implications to the Calvo-type rigidity modeling. Section 6 summarizes and concludes the discussion.

## 2 Adjustment Cost Structure Revisited

The inertial development in the change rate of a nominal variable  $X_t$  is driven by real adjustment costs of the form:

$$Q_{t+k}^x = \frac{\phi_x}{2} \left( \frac{X_{t+k}}{X_{t+k-1}} - \frac{X}{X} \right)^2 + \frac{v_x}{2} \left( \frac{X_{t+k}}{X_{t+k-1}} - \frac{X_{t+k-1}}{X_{t+k-2}} \right)^2 \quad \phi_x, v_x > 0 \quad (1)$$

where  $X_{t+k}$  is the choice variable of a monopolistic agent not explicitly indexed and  $X$  denotes the steady state level of this variable. The suppressed agent indexation makes clear that (1) is also an aggregate formulation due to symmetry assumptions. From the perspective of the decision period  $t$ , the agent rationally expects the following asymptotic and discounted stream of adjustments costs:

$$E_t \sum_{k=0}^{\infty} \left( \frac{1}{1+\xi} \right)^k Q_{t+k}^x \quad (2)$$

where  $\xi$  is the subjective time preference rate of the agent. Notice that setting  $\phi_x > 0, v_x = 0$  leads to the adjustment cost structure typically found in the literature. We refer to this basic quadratic formulation as the Hairault/Portier specification, as Hairault and Portier (1993) formulate the non-linear version of the adjustment costs introduced by Rotemberg (1982). A monopolistic economic agent optimizes in period  $t$  its target with respect to  $X_t$  and subject to its own demand function.

Moreover, equation (1) implies the emergence of menu costs whenever  $X_t$  is adjusted, forcing the agent to adopt an intertemporal perspective as formulated in (2). In the Hairault/Portier specification adjustment costs arise in case that the next periods' (rationally expected and discounted) level  $X_{t+1}$  differs from the current level  $X_t$ . Therefore, the agent will intend to smooth the chosen level of  $X_t$  over two periods along an intertemporal target optimization in order to reduce adjustment costs. For  $v_p > 0$ , adjustment costs disperse over three periods and the prevalence of the variable set in period  $t$  over the succeeding two periods renders a more complex intertemporal optimization problem for the agent. Particularly, the agent will have to form rational expectations concerning the variable  $X_{t+2}$  given the information set at period  $t$ . This is not found to be implausible since two periods ahead is not a considerable large amount of time if the quarterly time span is adopted as typically done in the New Keynesian literature. As for the cost structure itself ( $k = 0$ ), note first that as long as  $v_p > 0$ , the isolated equivalence  $X_t = X_{t-1}$  will not lead to  $Q_t^x = 0$  as in the Hairault/Portier specification:

$$Q_t^{x,I} = \frac{v_x}{2} \left( \frac{X_t}{X_{t-2}} - 1 \right)^2 \quad \text{for} \quad X_t = X_{t-1} \neq X_{t-2} \quad (3)$$

Therefore, the identity of the nominal variable to its last-period counterpart will not be sufficient to generate a flexible price environment. Note further that the isolated imposition of  $X_{t-1} = X_{t-2}$  implies:

$$Q_t^{x,II} = \frac{\phi_x}{2} \left( \frac{X_t}{X_{t-2}} - \frac{X}{X} \right)^2 + \frac{v_x}{2} \left( \frac{X_t}{X_{t-2}} - \frac{X_{t-1}}{X_{t-2}} \right)^2 \quad \text{for} \quad X_t \neq X_{t-1} = X_{t-2} \quad (4)$$

or written in terms of equation (3):

$$Q_t^{x,II} = \frac{\phi_x}{2} \left( \frac{X_t}{X_{t-2}} - \frac{X}{X} \right)^2 + Q_t^{x,I} \quad (5)$$

Therefore, we obtain an asymmetric cost structure in which the costs are higher  $Q_t^{x,II} > Q_t^{x,I}$  if the current level diverges from its last's periods value, the latter being equalized to its before-last level ( $X_t \neq X_{t-1} = X_{t-2}$ ). Finally, note that the adjustment cost structure (1) fulfills the desired property of null adjustment costs in the flexible nominal variable environment ( $X_t = X_{t-1} = X_{t-2}$ ).

### 3 Microeconomic Foundations

In the following sections the presented adjustment cost structure is embedded in a New Keynesian DSGE framework at the microeconomic level. This is the main distinction to the theoretical models developed so far in order to fit empirical characteristics at the aggregate level. The production side consists of a final-good producer and intermediate firms. Further agents are households, commercial banks, and a monetary authority. Intermediate goods are sold under monopolistic competition to the assembling production agent and the latter sells the resulting homogeneous final good to households under perfect competition market conditions. Households maximize a separable utility function asymptotically with respect to consumption, money and leisure in a similar manner as in Smets and Wouters (2003). We introduce internal habit formation in consumption, which is in line with Casares (2006). Moreover, labor supply is differentiated across households and offered under monopolistic competition to intermediate firms. The latter finance in advance labor cost with a portfolio of differentiated loan types. Therefore, we introduce monopolistic commercial banks as in Henzel et al. (2009) and Hülsewig et al. (2009).

#### 3.1 Final Good Production

The production in this sector results in a homogeneous good  $Y_t$  sold under perfect market conditions with a corresponding aggregate price index  $P_t$ . Input factors are monopolistically offered intermediate goods, where  $Y_t(i)$  is the input from an intermediate firm lying in the unit interval  $[0, 1]$ . The assembly across all types of intermediate goods towards the final good takes place according to a Dixit-Stiglitz type aggregator function:

$$Y_t = \left( \int_0^1 Y_t(i)^{\frac{\epsilon_p}{\epsilon_p-1}} di \right)^{\frac{\epsilon_p-1}{\epsilon_p}} \quad (6)$$

where  $\epsilon_p$  denotes the elasticity of substitution between intermediate good varieties. The final good producer maximizes its profits with respect to an input variety  $Y_t(i)$  and taking the CES production technology (6) into account. Real profits can be

formulated as:

$$Y_t = \int_0^1 \frac{P_t(i) Y_t(i)}{P_t} di \quad (7)$$

The resulting profit maximizing demand schedule for input variety  $i$  is:

$$Y_t(i) = \left( \frac{P_t(i)}{P_t} \right)^{-\epsilon_p} Y_t \quad (8)$$

Inserting this equation into (6) yields a Dixit-Stiglitz type price index for the bundle  $Y_t$ :

$$P_t = \left( \int_0^1 P_t(i)^{1-\epsilon_p} di \right)^{\frac{1}{1-\epsilon_p}} \quad (9)$$

### 3.2 Intermediate Good Producers

Each commodity  $Y_t(i)$  is produced by a single firm with a decreasing returns to labor hours technology <sup>3</sup>:

$$Y_t(i) = N_t(i)^{1-\alpha} \quad , \quad 0 < \alpha < 1 \quad (10)$$

Nominal labor cost  $W_t N_t(i)$  is assumed to be prefinanced at the beginning of period  $t$  by the type-differentiated nominal loan volume  $L_t(i)$ . Repayment takes place after one period at the gross loan rate  $R_t^L$ . The total operational cost of firm  $i$  is therefore given by:

$$TC_t(i) = \frac{W_t N_t(i)}{P_t} R_t^L = \frac{L_t(i)}{P_t} R_t^L \quad (11)$$

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<sup>3</sup> We abstract from capital rental services for the sake of simplicity but without loss of generality.



An intratemporal total cost minimization procedure of the firm subject to (10) yields the firm-specific real marginal cost:

$$MC_t(i) = \left( \frac{1}{1-\alpha} \right) \frac{W_t}{P_t} R_t^L Y_t(i)^{\frac{\alpha}{1-\alpha}} \quad (12)$$

A firm  $i \in [0, 1]$  chooses its own price  $P_t(i)$  in order to maximize monopolistic real profits. The own demand schedule to be taken into account is given by (8). Moreover, the firm faces real quadratic costs of price adjustment as formulated under section 2. Specifically, we have for  $k = 0$ :

$$Q_t^p(i) = \frac{\psi_p}{2} \left( \frac{P_t(i)}{P_{t-1}(i)} - \pi^p \right)^2 + \frac{v_p}{2} \left( \frac{P_t(i)}{P_{t-1}(i)} - \frac{P_{t-1}(i)}{P_{t-2}(i)} \right)^2 \quad (13)$$

where  $\pi^p = 1$  denotes the steady state gross inflation rate in the absence of trend inflation. The real profits of an intermediate firm can be written as:

$$E_t \sum_{k=0}^{\infty} \Delta_{t,t+k} \left[ \frac{P_{t+k}(i) Y_{t+k}(i)}{P_{t+k}} - MC_{t+k}(i) Y_{t+k}(i) - Q_{t+k}^p(i) \right] \quad (14)$$

Inserting the individual demand schedule and the adjustment cost formulation into the intertemporal profit expression and taking the first-order derivative with respect to  $P_t(i)$  leads to the optimal price setting pattern from the viewpoint of firm  $i$ :

$$\begin{aligned} \left( \frac{P_t(i)}{P_{t-1}(i)} - \pi^p \right) \frac{P_t(i)}{P_{t-1}(i)} &= \frac{\epsilon_p Y_t}{\psi_p} \left( MC_t(i) - \frac{1}{\mu_p} \right) - \frac{v_p}{\psi_p} \left( \frac{P_t(i)}{P_{t-1}(i)} - \frac{P_{t-1}(i)}{P_{t-2}(i)} \right) \frac{P_t(i)}{P_{t-1}(i)} \\ &+ E_t \left[ \frac{\Delta_{t,t+1}}{\Delta_{t,t}} \left( \left( \frac{P_{t+1}(i)}{P_t(i)} - \pi^p \right) \frac{P_{t+1}(i)}{P_t(i)} \right. \right. \\ &\quad \left. \left. + \frac{v_p}{\psi_p} \left( \frac{P_{t+1}(i)}{P_t(i)} - \frac{P_t(i)}{P_{t-1}(i)} \right) \left( \frac{P_{t+1}(i)}{P_t(i)} + \frac{P_t(i)}{P_{t-1}(i)} \right) \right) \right] \\ &- E_t \left[ \frac{\Delta_{t,t+2}}{\Delta_{t,t}} \frac{v_p}{\psi_p} \left( \frac{P_{t+2}(i)}{P_{t+1}(i)} - \frac{P_{t+1}(i)}{P_t(i)} \right) \frac{P_{t+1}(i)}{P_t(i)} \right] \end{aligned} \quad (15)$$

where  $\mu_p = \epsilon_p / (\epsilon_p - 1)$  is the constant monopolistic markup of the firms.

Since households own firms, the (aggregate) marginal utility of consumption relation  $\Delta_{t,t+k} = \beta^k \left( \frac{\partial U_{t+k}/\partial C_{t+k}}{\partial U_t/\partial C_t} \right)$  represents the relevant stochastic discount factor for current and future firm profits in real terms. Note that under full price flexibility ( $\psi_p = 0$ ;  $P_{t-2}(i) = P_{t-1}(i) = P_t(i) = P_{t+1}(i) = P_{t+2}(i)$ ) an intermediate firm sets its price as a markup over its nominal marginal cost  $P_t MC_t(i)$ .

### 3.3 Commercial Banks

We introduce monopolistic loan supply as in Henzel et al. (2009) and Hülsewig et al. (2009). The differentiation and monopolistic competition in loan types may appear from tight customer-banks relationships or specialization in certain geographical regions (Carletti et al. (2007)). However, we depart from their Calvo-type modeling of lending frictions and assume the specification presented in section 2 instead.

The real profits of a commercial bank  $l \in [0, 1]$  can be formulated as:

$$E_t \sum_{k=0}^{\infty} \Delta_{t,t+k} \left[ \frac{R_{t+k}^L(l) L_{t+k}(l)}{P_{t+k}} - TC_{t+k}^r(l) - Q_{t+k}^R(l) \right] \quad (16)$$

where the balance sheet equalizes the nominal loan volume to the sum of nominal deposits  $d_t(l)$  and the net position in the money market  $B_t(l)$ :

$$L_t(l) = d_t(l) + B_t(l) \quad (17)$$

Since deposits and money market credits are assumed to be perfect substitutes (Freixas et. al (2000)), their gross interest rates are identical ( $R_t^d = R_t^M$ ). Total real cost arising from the placing of loans can then be written as:

$$TC_t(l) = \frac{d_t(l)}{P_t} R_t^d + \frac{B_t(l)}{P_t} R_t^M = \left( \frac{d_t(l) + B_t(l)}{P_t} \right) R_t^M = \left( \frac{L_t(l)}{P_t} \right) R_t^M \quad (18)$$

The loan demand schedule faced by the monopolistic bank can be shown to be:

$$L_t(l) = \left( \frac{R_t^L(l)}{R_t^L} \right)^{-\zeta} L_t \quad (19)$$

Moreover, the bank faces real quadratic costs of loan rate adjustment as formulated

under section 2. In terms of nominal loan rate deviations this implies:

$$Q_t^r(l) = \frac{\psi_r}{2} \left( \frac{R_t^L(l)}{R_{t-1}^L(l)} - 1 \right)^2 + \frac{v_r}{2} \left( \frac{R_t(l)}{R_{t-1}^L(l)} - \frac{R_{t-1}^L(l)}{R_{t-2}^L(l)} \right)^2 \quad (20)$$

Inserting the last two constraints together with  $TC_t(l)$  into the banks' profit formulation and taking the first-order derivative with respect to  $R_t^L(l)$  leads to the optimal loan rate setting pattern from the viewpoint of bank  $l$ :

$$\begin{aligned} \left( \frac{R_t^L(l)}{R_{t-1}^L(l)} - 1 \right) \frac{R_t^L(l)}{R_{t-1}^L(l)} &= \frac{\zeta N_t W_t}{\psi_r P_t} \left( R_t^M - \frac{R_t^L}{\Xi} \right) - \frac{v_r}{\psi_r} \left( \frac{R_t^L(l)}{R_{t-1}^L(l)} - \frac{R_{t-1}^L(l)}{R_{t-2}^L(l)} \right) \frac{R_t^L(l)}{R_{t-1}^L(l)} \\ &+ E_t \left[ \frac{\Delta_{t,t+1}}{\Delta_{t,t}} \left( \left( \frac{R_{t+1}^L(l)}{R_t^L(l)} - 1 \right) \frac{R_{t+1}^L(l)}{R_t^L(l)} \right. \right. \\ &\quad \left. \left. + \frac{v_r}{\psi_r} \left( \frac{R_{t+1}^L(l)}{R_t^L(l)} - \frac{R_t^L(l)}{R_{t-1}^L(l)} \right) \left( \frac{R_{t+1}^L(l)}{R_t^L(l)} + \frac{R_t^L(l)}{R_{t-1}^L(l)} \right) \right) \right] \\ &- E_t \left[ \frac{\Delta_{t,t+2}}{\Delta_{t,t}} \frac{v_r}{\psi_r} \left( \frac{R_{t+2}^L(l)}{R_{t+1}^L(l)} - \frac{R_{t+1}^L(l)}{R_t^L(l)} \right) \frac{R_{t+1}^L(l)}{R_t^L(l)} \right] \end{aligned} \quad (21)$$

### 3.4 Households

There is a continuum of households in the unit interval  $[0, 1]$ , each supplying one specific variety of labor  $j$  in a monopolistic manner. A household aims to maximize its expected and discounted sum of periodical utilities:

$$E_t \sum_{k=0}^{\infty} \beta^k U_{t+k} \quad (22)$$

The periodical utility functional form is separable in consumption, labor, and real balances. Moreover, current consumption is relative to a time-varying internal habit term:

$$U_{t+k} = \frac{(C_{t+k}(j) - h C_{t+k-1}(j))^{1-\sigma}}{1-\sigma} + \frac{(M_{t+k}(j)/P_{t+k})^{1-\nu}}{1-\nu} - \frac{(N_{t+k}(j))^{1+\eta}}{1+\eta} \quad (23)$$

where  $\sigma$  is the coefficient of relative risk aversion (or the inverse of the intertemporal elasticity of substitution in consumption). The coefficient  $\nu$  represents the inverse

of the elasticity of real money holdings with respect to the interest rate and  $\eta$  is the inverse of the sensibility of labor supply with respect to the real wage. The household chooses its optimal demand path for consumption  $C_t(j)$ , money holdings  $M_t(j)$  and deposits  $d_t(j)$  by maximizing (22) subject to the following intertemporal real budget constraint:

$$E_t \sum_{k=0}^{\infty} \beta^k \left[ C_{t+k}(j) + \frac{d_{t+k}(j)}{P_{t+k}} \right] = E_t \sum_{k=0}^{\infty} \beta^k \left[ \frac{W_{t+k}(j)N_{t+k}(j)}{P_{t+k}} + R_{t+k-1}^d \frac{d_{t+k-1}(j)}{P_{t+k}} \right. \\ \left. + Div_{t+k}^r(j) - Q_{t+k}^w(j) \right] \quad (24)$$

where  $Div_{t+k}^r(j)$  are the dividends derived from firms and commercial banks. Combining the resulting first-order conditions with respect to  $C_t(j)$  and  $d_t(j)$  leads to the following consumption Euler equation of household  $j$  with internal habit formation:

$$\beta E_t \left[ \frac{R_t^d}{\pi_{t+1}^p} \right] = E_t \left[ \frac{\lambda_t(j)}{\lambda_{t+1}(j)} \right] \quad (25)$$

Further, the optimality conditions concerning  $M_t(j)$  and  $d_t(j)$  allow for an individual real money demand formulation of the following form:

$$\left( \frac{M_t(j)}{P_t} \right)^{-\nu} = E_t \left[ \lambda_t(j) \left( 1 - \frac{1}{R_t^d} \right) \right] \quad (26)$$

The variable  $\lambda_t(j)$  denotes the multiplier of the corresponding lagrange problem given as the individual marginal utility of consumption:

$$\lambda_{t+k}(j) = \partial U_{t+k}(j) / \partial C_{t+k}(j) \\ = (C_{t+k}(j) - hC_{t+k-1}(j))^{-\sigma} - \beta h (C_{t+k+1}(j) - hC_{t+k}(j))^{-\sigma} \quad (27)$$

The labor supplying household chooses its own monopolistic nominal wage  $W_t(j)$  optimally taking into account its individual labor demand schedule.

The latter can be derived as:

$$N_t(j) = \left( \frac{W_t(j)}{W_t} \right)^{-\epsilon_w} N_t \quad (28)$$

where

$$N_t = \left( \int_0^1 N_t(j)^{\frac{\epsilon_w}{\epsilon_w-1}} di \right)^{\frac{\epsilon_w-1}{\epsilon_w}} \quad (29)$$

and

$$W_t = \left( \int_0^1 W_t(j)^{1-\epsilon_w} dj \right)^{\frac{1}{1-\epsilon_w}} \quad (30)$$

are Dixit-Stiglitz formulations for aggregate labor demand and the aggregate nominal wage index. A household faces real costs of nominal wage adjustment as introduced in section 2. For  $k = 0$  this implies the following additional constraint:

$$Q_t^w(j) = \frac{\psi_w}{2} \left( \frac{W_t(j)}{W_{t-1}(j)} - \pi^w \right)^2 + \frac{v_w}{2} \left( \frac{W_t(j)}{W_{t-1}(j)} - \frac{W_{t-1}(j)}{W_{t-2}(j)} \right)^2 \quad (31)$$

Inserting (28) and (31) into the utility and budget constraint leads after the optimization to the wage setting pattern from the viewpoint of household  $j$ :

$$\begin{aligned} \left( \frac{W_t(j)}{W_{t-1}(j)} - \pi^w \right) \frac{W_t(j)}{W_{t-1}(j)} &= \frac{(\epsilon_w - 1) N_t}{\psi_w} \left( \mu_w MRS_t(j) - \frac{W_t(j)}{P_t} \right) \\ &\quad - \frac{v_w}{\psi_w} \left( \frac{W_t(j)}{W_{t-1}(j)} - \frac{W_{t-1}(j)}{W_{t-2}(j)} \right) \frac{W_t(j)}{W_{t-1}(j)} \\ &\quad + \beta E_t \left[ \frac{\lambda_{t+1}(j)}{\lambda_t(j)} \left( \left( \frac{W_{t+1}(j)}{W_t(j)} - \pi^w \right) \frac{W_{t+1}(j)}{W_t(j)} \right. \right. \\ &\quad \left. \left. + \frac{v_w}{\psi_w} \left( \frac{W_{t+1}(j)}{W_t(j)} - \frac{W_t(j)}{W_{t-1}(j)} \right) \left( \frac{W_{t+1}(j)}{W_t(j)} + \frac{W_t(j)}{W_{t-1}(j)} \right) \right) \right] \\ &\quad - \beta^2 E_t \left[ \frac{\lambda_{t+2}(j)}{\lambda_t(j)} \frac{v_w}{\psi_w} \left( \frac{W_{t+2}(j)}{W_{t+1}(j)} - \frac{W_{t+1}(j)}{W_t(j)} \right) \frac{W_{t+1}(j)}{W_t(j)} \right] \end{aligned} \quad (32)$$

where  $\mu_w = (\epsilon_w/\epsilon_w - 1)$  is the constant monopolistic markup of households. Note that under full price flexibility ( $\psi_w = 0$  ;  $W_{t-2}(j) = W_{t-1}(j) = W_t(j) = W_{t+1}(j) = W_{t+2}(j)$ ) a household sets its nominal wage as a markup over its monetarized marginal rate of substitution  $P_t MRS_t(j)$ , where the real counterpart is given by:

$$MRS_t(j) = -\frac{\partial U_t(j)/\partial N_t(j)}{\partial U_t(j)/\partial C_t(j)} = \frac{N_t^\eta(j)}{\lambda_t(j)} \quad (33)$$

### 3.5 Monetary Policy

The central bank is assumed to follow a Taylor rule (see Taylor (1993)). We consider the non-linear deviation of the gross interest rate from its steady state counterpart  $R$  as the control instrument. The reaction parameters with respect to real output and inflation variations are given by  $\delta_\pi$ ,  $\delta_y$ , while  $\phi$  acts as a smoothing parameter:

$$\left(\frac{R_t}{R}\right) = \left(\left(\frac{\pi_t^p}{\pi^p}\right)^{\delta_\pi} \left(\frac{Y_t}{Y}\right)^{\delta_y}\right)^{1-\phi} \left(\frac{R_{t-1}}{R}\right)^\phi \left(\frac{Z_t}{Z}\right) \quad (34)$$

The shock variable  $Z_t$  depicts an unsystematic deviation from the policy rule and is governed by the following first-order autoregressive process with a stochastic i.i.d. shock impulse variable  $\tilde{e}$ :

$$Z_t = (Z_{t-1})^\rho (Z)^{1-\rho} \exp\{\tilde{e}\} \quad , \quad \rho \in [0, 1) \quad , \quad \tilde{e}_t \sim N(0, 1) \quad (35)$$

A very simplifying assumption is the complete control of interbank money interest rates by the central bank instrument:

$$R_t = R_t^M \quad (36)$$

## 4 Aggregation and Log-Linearization

In the following a symmetric macroeconomic equilibrium is assumed. Moreover, we impose a market clearing in the goods, labor, and loan market in conjunction with a neutral net position of households and banks ( $d_t = B_t \equiv 0$ ). An equilibrated money market is obtained by an endogenous money supply to meet money demand at given interest rates. The symmetry assumption implies that all firms are confronted with an identical profit maximization problem when setting their own price. The same applies for households concerning their nominal wage and for commercial banks when adjusting their gross loan rate. Consequently, we have the following set of aggregation conditions:

$$P_t(i) \equiv P_t \quad (37) \qquad Y_t(i) = Y_t \quad (38)$$

$$W_t(j) \equiv W_t \quad (39) \qquad N_t(j) = N_t \quad (40)$$

$$R_t(l) \equiv R_t \quad (41) \qquad L_t(l) = L_t \quad (42)$$

$$C_t(j) \equiv C_t \quad (43) \qquad Div_t(j) \equiv Div_t \quad (44)$$

$$B_t(l) \equiv B_t \equiv 0 \quad (45) \qquad d_t(j) \equiv d_t \equiv 0 \quad (46)$$

The conditions stated above simplify the behavioral equations of private agents significantly and allow for an aggregate economy representation. Concerning the individual price setting behavior stated in (15), we obtain on the aggregate level:

$$\begin{aligned} \left( \frac{P_t}{P_{t-1}} - \pi^p \right) \frac{P_t}{P_{t-1}} &= \frac{\epsilon_p Y_t}{\psi_p} \left( MC_t - \frac{1}{\mu_p} \right) - \frac{v_p}{\psi_p} \left( \frac{P_t}{P_{t-1}} - \frac{P_{t-1}}{P_{t-2}} \right) \frac{P_t}{P_{t-1}} \\ &+ E_t \left[ \frac{\Delta_{t,t+1}}{\Delta_{t,t}} \left( \left( \frac{P_{t+1}}{P_t} - \pi^p \right) \frac{P_{t+1}}{P_t} \right. \right. \\ &\quad \left. \left. + \frac{v_p}{\psi_p} \left( \frac{P_{t+1}}{P_t} - \frac{P_t}{P_{t-1}} \right) \left( \frac{P_{t+1}}{P_t} + \frac{P_t}{P_{t-1}} \right) \right) \right] \\ &- E_t \left[ \frac{\Delta_{t,t+2}}{\Delta_{t,t}} \frac{v_p}{\psi_p} \left( \frac{P_{t+2}}{P_{t+1}} - \frac{P_{t+1}}{P_t} \right) \frac{P_{t+1}}{P_t} \right] \end{aligned} \quad (47)$$

where aggregate real marginal cost are given according to (12) as:

$$MC_t = \left( \frac{1}{1-\alpha} \right) \frac{W_t}{P_t} R_t^L Y_t^{1-\alpha} \quad (48)$$

By defining the gross price inflation rate as  $\pi_{t+k}^p \equiv \left( 1 + \frac{P_{t+k} - P_{t+k-1}}{P_{t+k-1}} \right) = \frac{P_{t+k}}{P_{t+k-1}}$  and expressing the stochastic discount factors in terms of marginal household utility, we arrive at the following non-linear Phillips curve for price inflation:

$$\begin{aligned} (\pi_t^p - \pi^p) \pi_t^p &= \frac{\epsilon_p Y_t}{\psi_p} \left( MC_t - \frac{1}{\mu_p} \right) - \frac{v_p}{\psi_p} (\pi_t^p - \pi_{t-1}^p) \pi_t^p \\ &+ \beta E_t \left[ \frac{(C_{t+1} - hC_t)^{-\sigma} - \beta h (C_{t+2} - hC_{t+1})^{-\sigma}}{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}} \left( (\pi_{t+1}^p - \pi_p) \pi_{t+1}^p \right. \right. \\ &\quad \left. \left. + \frac{v_p}{\psi_p} (\pi_{t+1}^p - \pi_t^p) (\pi_{t+1}^p + \pi_t^p) \right) \right] \\ &- \beta^2 E_t \left[ \frac{(C_{t+2} - hC_{t+1})^{-\sigma} - \beta h (C_{t+3} - hC_{t+2})^{-\sigma}}{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}} \frac{v_p}{\psi_p} (\pi_{t+2}^p - \pi_{t+1}^p) \pi_{t+1}^p \right] \end{aligned} \quad (49)$$

A similar procedure delivers on the grounds of individual nominal wage setting (32):

$$\begin{aligned} \left( \frac{W_t}{W_{t-1}} - \pi^w \right) \frac{W_t}{W_{t-1}} &= \frac{(\epsilon_w - 1) N_t}{\psi_w} \left( \mu_w MRS_t - \frac{W_t}{P_t} \right) - \frac{v_w}{\psi_w} \left( \frac{W_t}{W_{t-1}} - \frac{W_{t-1}}{W_{t-2}} \right) \frac{W_t}{W_{t-1}} \\ &+ \beta E_t \left[ \frac{\lambda_{t+1}}{\lambda_t} \left( \left( \frac{W_{t+1}}{W_t} - \pi_w \right) \frac{W_{t+1}}{W_t} \right. \right. \\ &\quad \left. \left. + \frac{v_w}{\psi_w} \left( \frac{W_{t+1}}{W_t} - \frac{W_t}{W_{t-1}} \right) \left( \frac{W_{t+1}}{W_t} + \frac{W_t}{W_{t-1}} \right) \right) \right] \\ &- \beta^2 E_t \left[ \frac{\lambda_{t+2}}{\lambda_t} \frac{v_w}{\psi_w} \left( \frac{W_{t+2}}{W_{t+1}} - \frac{W_{t+1}}{W_t} \right) \frac{W_{t+1}}{W_t} \right] \end{aligned} \quad (50)$$



where the aggregate marginal rate of substitution is given according to (33) as:

$$MRS_t = N_t^\eta \left( (C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma} \right)^{-1} \quad (51)$$

Considering the gross wage inflation rate as  $\pi_{t+k}^w \equiv \left( 1 + \frac{W_{t+k} - W_{t+k-1}}{W_{t+k-1}} \right) = \frac{W_{t+k}}{W_{t+k-1}}$  and substituting stochastic discount factors, we arrive at the following non-linear Phillips curve for nominal wage inflation:

$$\begin{aligned} (\pi_t^w - \pi^w) \pi_t^w &= \frac{(\epsilon_w - 1) N_t}{\psi_w} \left( \mu_w MRS_t - \frac{W_t}{P_t} \right) - \frac{v_w}{\psi_w} (\pi_t^w - \pi_{t-1}^w) \pi_t^w \\ &+ \beta E_t \left[ \frac{(C_{t+1} - hC_t)^{-\sigma} - \beta h (C_{t+2} - hC_{t+1})^{-\sigma}}{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}} \left( (\pi_{t+1}^w - \pi_w) \pi_{t+1}^w \right. \right. \\ &\quad \left. \left. + \frac{v_w}{\psi_w} (\pi_{t+1}^w - \pi^w) (\pi_{t+1}^w + \pi_t^w) \right) \right] \\ &- \beta^2 E_t \left[ \frac{(C_{t+2} - hC_{t+1})^{-\sigma} - \beta h (C_{t+3} - hC_{t+2})^{-\sigma}}{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}} \frac{v_w}{\psi_w} (\pi_{t+2}^w - \pi_{t+1}^w) \pi_{t+1}^w \right] \end{aligned} \quad (52)$$

The optimal loan rate setting from the viewpoint of a commercial bank (21) delivers the aggregate loan rate behavior as:

$$\begin{aligned} \left( \frac{R_t^L}{R_{t-1}^L} - 1 \right) \frac{R_t^L}{R_{t-1}^L} &= \frac{\zeta N_t W_t}{\psi_r P_t} \left( R_t^M - \frac{R_t^L}{\Xi} \right) - \frac{v_r}{\psi_r} \left( \frac{R_t^L}{R_{t-1}^L} - \frac{R_{t-1}^L}{R_{t-2}^L} \right) \frac{R_t^L}{R_{t-1}^L} \\ &+ E_t \left[ \frac{(C_{t+1} - hC_t)^{-\sigma} - \beta h (C_{t+2} - hC_{t+1})^{-\sigma}}{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}} \left( \left( \frac{R_{t+1}^L}{R_t^L} - 1 \right) \frac{R_{t+1}^L}{R_t^L} \right. \right. \\ &\quad \left. \left. + \frac{v_r}{\psi_r} \left( \frac{R_{t+1}^L}{R_t^L} - \frac{R_t^L}{R_{t-1}^L} \right) \left( \frac{R_{t+1}^L}{R_t^L} + \frac{R_t^L}{R_{t-1}^L} \right) \right) \right] \\ &- E_t \left[ \frac{(C_{t+2} - hC_{t+1})^{-\sigma} - \beta h (C_{t+3} - hC_{t+2})^{-\sigma}}{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}} \frac{v_r}{\psi_r} \left( \frac{R_{t+2}^L}{R_{t+1}^L} - \frac{R_{t+1}^L}{R_t^L} \right) \frac{R_{t+1}^L}{R_t^L} \right] \end{aligned} \quad (53)$$

and we refrain from any further simplification as done above since the loan rate itself is of interest rather than its change rate over time. The consumption Euler equation on the individual level (25) is rendered by our aggregation assumptions to be:

$$\beta E_t \left[ \frac{R_t^d}{\pi_{t+1}^p} \right] = E_t \left[ \frac{(C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma}}{(C_{t+1} - hC_t)^{-\sigma} - \beta h (C_{t+2} - hC_{t+1})^{-\sigma}} \right] \quad (54)$$

Similarly, considering (26) yields aggregate real money demand as:

$$\left( \frac{M_t}{P_t} \right)^{-\nu} = E_t \left[ \left( (C_t - hC_{t-1})^{-\sigma} - \beta h (C_{t+1} - hC_t)^{-\sigma} \right) \left( 1 - \frac{1}{R_t^d} \right) \right] \quad (55)$$

According to the production function (10), aggregate employment evolves as:

$$N_t = Y_t^{\frac{1}{1-\alpha}} \quad , \quad 0 < \alpha < 1 \quad (56)$$

Note that the coexistence of nominal wage setting frictions with aggregate price rigidities leads to sluggish real wage movements over time. This is visualized by the following inflation identity:

$$\frac{W_t}{P_t} = \frac{W_t}{P_t} \frac{W_{t-1}}{P_{t-1}} \frac{P_{t-1}}{W_{t-1}} = \frac{W_{t-1}}{P_{t-1}} \frac{\pi_t^w}{\pi_t^p} \quad (57)$$

Finally, the aggregate resource constraint can be derived directly from the periodical household budget constraint (24) in its aggregate version. After eliminating the profit transfers stemming from firms and banks, one arrives at:

$$Y_t = C_t + \frac{\psi_p}{2} (\pi_t^p - \pi^p)^2 + \frac{\nu_p}{\psi_p} (\pi_t^p - \pi_{t-1}^p)^2 + \frac{\psi_w}{2} (\pi_t^w - \pi^w)^2 + \frac{\nu_w}{\psi_p} (\pi_t^w - \pi_{t-1}^w)^2 \\ + \frac{\psi_r}{2} \left( \frac{R_t^L}{R_{t-1}^L} - 1 \right)^2 + \frac{\nu_r}{\psi_r} \left( \frac{R_t^L}{R_{t-1}^L} - \frac{R_{t-1}^L}{R_{t-2}^L} \right)^2 \quad (58)$$

We simplify the aggregate expressions stated above by applying a first-order Taylor expansion in logarithms around the deterministic and non-inflationary steady state<sup>4</sup>. For a variable  $V_t$  and its steady state counterpart  $V$ , we then have  $\left(\frac{V_t-V}{V}\right) \approx \log(V_t) - \log(V) \equiv \hat{V}_t$ , where a hat over a variable denotes the logarithmic deviation from its steady state value. The non-linear Phillips curve for price inflation (49) can then be rewritten as:

$$\hat{\pi}_t^p = \gamma_1 \hat{\pi}_{t-1}^p + \gamma_2 E_t[\hat{\pi}_{t+1}^p] - \gamma_3 E_t[\hat{\pi}_{t+2}^p] + \gamma_4 \widehat{MC}_t \quad (59)$$

$$\gamma_1 = \frac{v_p}{v_p(1+2\beta) + \psi_p} \quad (60) \quad \gamma_2 = \frac{v_p(2+\beta)\beta + \psi_p\beta}{v_p(1+2\beta) + \psi_p} \quad (61)$$

$$\gamma_3 = \frac{v_p\beta^2}{v_p(1+2\beta) + \psi_p} \quad (62) \quad \gamma_4 = \frac{(\epsilon_p - 1)Y}{v_p(1+2\beta) + \psi_p} \quad (63)$$

The variable  $Y$  gives the steady state real output level which can be obtained by solving for the time independent relationships implied by the model:

$$Y = \left( \frac{(1-\alpha)(1-\beta h)\beta}{\mu_p \mu_w \Xi (1-h)^\sigma} \right)^{\frac{1-\alpha}{\alpha+\eta+\sigma(1-\alpha)}} \quad (64)$$

A log-linearization of aggregate real marginal cost (48) delivers:

$$\widehat{MC}_t = \hat{W}_t - \hat{P}_t + \hat{R}_t^L + \left( \frac{\alpha}{1-\alpha} \right) \hat{Y}_t \quad (65)$$

A few words are in order concerning the price inflation relation stated in (59). Note first, that our New Keynesian Phillips curve is not only hybrid, but involves a negative inflation expectation term two periods ahead ( $E_t[\pi_{t+2}^p]$ ) conditional on the information set available in period  $t$ . This is a direct result of the adjustment cost

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<sup>4</sup> Note that we do not pursue any normative insights in terms of welfare but only business cycle characterizations. While the former are not reliable under our approximation order of one, the latter can well be inspected.

structure presented in section 2. Second, the parameter  $v_p$  relates the last period inflation rate  $\pi_{t-1}^p$  to the two-period-ahead expectation since setting  $v_p = 0$  eliminates both terms and our inflation curve collapses to the traditional forward-looking New Keynesian Phillips curve. Third, we obtain the desirable property for the inflation weights  $\gamma_1 + \gamma_2 + \gamma_3 = 1$ . Proceeding as done so far, we derive the following log-linear relationship for the wage inflation Phillips curve stated in (52):

$$\hat{\pi}_t^w = \kappa_1 \hat{\pi}_{t-1}^w + \kappa_2 E_t [\hat{\pi}_{t+1}^w] - \kappa_3 E_t [\hat{\pi}_{t+2}^w] + \kappa_4 (\overline{MRS}_t - (\hat{W}_t - P_t)) \quad (66)$$

$$\kappa_1 = \frac{v_w}{v_w (1 + 2\beta) + \psi_w} \quad (67)$$

$$\kappa_2 = \frac{v_w (2 + \beta) \beta + \psi_w \beta}{v_w (1 + 2\beta) + \psi_w} \quad (68)$$

$$\kappa_3 = \frac{v_w \beta^2}{v_w (1 + 2\beta) + \psi_w} \quad (69)$$

$$\kappa_4 = \frac{(\epsilon_w - 1)}{v_w (1 + 2\beta) + \psi_w} \frac{W}{P} N \quad (70)$$

The steady state employment and real wage expressions entering the equation above are:

$$N = \left( \frac{(1 - \alpha) (1 - \beta h) \beta}{\mu_p \mu_w \Xi (1 - h)^\sigma} \right)^{\frac{1}{\alpha + \eta + \sigma(1 - \alpha)}} \quad (71)$$

$$\frac{W}{P} = \frac{\mu_w (1 - h)^\sigma}{1 - \beta h} \left( \frac{(1 - \alpha) (1 - \beta h) \beta}{\mu_p \mu_w \Xi (1 - h)^\sigma} \right)^{\frac{1}{\eta + \sigma(1 - \alpha)}} \quad (72)$$

Note that  $\kappa_1 + \kappa_2 + \kappa_3 = 1$  and by setting  $v_w = 0$  the nominal wage inflation Phillips curve reverts to its purely forward-looking counterpart. Further, the marginal rate of substitution determining wage inflation can be calculated in logarithmic deviations as:

$$\overline{MRS}_t = \eta \hat{N}_t + \iota_1 \hat{C}_t - \iota_2 \hat{C}_{t-1} - \iota_3 E_t [\hat{C}_{t+1}] \quad (73)$$

$$\iota_1 = \frac{\sigma (1 + \beta h^2)}{(1 - h) (1 - \beta h)} \quad (74)$$

$$\iota_2 = \frac{h\sigma}{(1 - h) (1 - \beta h)} \quad (75)$$

$$\iota_3 = \frac{\sigma\beta h}{(1-h)(1-\beta h)} \quad (76)$$

where an internal habit consumption parameter  $h = 0$  eliminates all intertemporal consumption relations in the marginal rate of substitution. The log-linear dynamic equation for the aggregate loan rate can analogously be calculated as:

$$\hat{R}_t^L = \varphi_1 \hat{R}_{t-1}^L - \varphi_2 \hat{R}_{t-2}^L + \varphi_3 E_t[\hat{R}_{t+1}^L] - \varphi_4 E_t[\hat{R}_{t+2}^L] + \varphi_5 \hat{R}_t^M \quad (77)$$

$$\varphi_1 = \frac{v_r(2(1+\beta)) + \psi_r}{v_r(1+\beta(4+\beta)) + \psi_r(1+\beta) + \zeta N(W/P)R^M} \quad (78)$$

$$\varphi_2 = \frac{v_r}{v_r(1+\beta(4+\beta)) + \psi_r(1+\beta) + \zeta N(W/P)R^M} \quad (79)$$

$$\varphi_3 = \frac{v_r(2\beta(1+\beta)) + \psi_r\beta}{v_r(1+\beta(4+\beta)) + \psi_r(1+\beta) + \zeta N(W/P)R^M} \quad (80)$$

$$\varphi_4 = \frac{v_r\beta^2}{v_r(1+\beta(4+\beta)) + \psi_r(1+\beta) + \zeta N(W/P)R^M} \quad (81)$$

$$\varphi_5 = \frac{\zeta N(W/P)R^M}{v_r(1+\beta(4+\beta)) + \psi_r(1+\beta) + \zeta N(W/P)R^M} \quad (82)$$

where the steady state interest rate factor is:

$$R^M = \frac{\pi^p}{\beta} = \frac{\pi^w}{\beta} = \frac{1}{\beta} \quad (83)$$

Again, setting  $v_r = 0$  eliminates the two-period lagged aggregate loan rate  $\hat{R}_{t-1}^L$  as well as its two-period ahead expectation  $E_t[\hat{R}_{t+2}^L]$ . This renders a purely forward-looking loan rate Phillips curve, when considering the logarithmic change in the loan rate  $\hat{R}_t^L - \hat{R}_{t-1}^L$ .

From equation (54), we obtain a standard Euler consumption equation with internal habit formation in log-deviations:

$$\hat{C}_t = \Theta_1 \hat{C}_{t-1} + \Theta_2 E_t [\hat{C}_{t+1}] - \Theta_3 E_t [\hat{C}_{t+2}] - \Theta_4 (\hat{R}_t^d - E_t [\hat{\pi}_{t+1}^p]) \quad (84)$$

$$\Theta_1 = \frac{h}{1+h(1+\beta h)} \quad (85) \quad \Theta_2 = \frac{1+\beta h(1+h)}{1+h(1+\beta h)} \quad (86)$$

$$\Theta_3 = \frac{\beta h}{1+h(1+\beta h)} \quad (87) \quad \Theta_4 = \frac{(1-h)(1-\beta h)}{\sigma(1+h(1+\beta h))} \quad (88)$$

Similarly, the aggregate money demand expression (55) can be rewritten as:

$$\hat{M}_t - \hat{P}_t = \Phi_1 \hat{C}_t - \Phi_2 \hat{C}_{t-1} - \Phi_3 E_t [\hat{C}_{t+1}] - \Phi_4 \hat{R}_t^d \quad (89)$$

$$\Phi_1 = \frac{\sigma(1+\beta h^2)}{\nu(1-h)(1-\beta h)} \quad (90) \quad \Phi_2 = \frac{\sigma h}{\nu(1-h)(1-\beta h)} \quad (91)$$

$$\Phi_3 = \frac{\sigma \beta h}{\nu(1-h)(1-\beta h)} \quad (92) \quad \Phi_4 = \frac{\beta}{\nu(1-\beta)} \quad (93)$$

Again, setting  $h = 0$  eliminates all lagged intertemporal consumption relations in the the aggregate consumption Euler equation and in the aggregate money demand equation. Aggregate employment and the aggregate real wage evolve in log-linear terms as:

$$\hat{N}_t = \frac{1}{1-\alpha} \hat{Y}_t \quad , \quad 0 < \alpha < 1 \quad (94)$$

$$\hat{W}_t - \hat{P}_t = \hat{W}_{t-1} - \hat{P}_{t-1} + \hat{\pi}_t^w - \hat{\pi}_t^p \quad (95)$$

Note that the adjustment cost inefficiencies absorbing output in (58) vanish not only the long run, but also when considering log-deviations:

$$\hat{Y}_t = \hat{C}_t \quad (96)$$

Finally, we rewrite the shock-augmented Taylor rule (34) in the form that is standardly applied in the literature:

$$\hat{R}_t = (1 - \phi) (\delta_\pi \hat{\pi}_t^p + \delta_y \hat{Y}_t) + \phi \hat{R}_{t-1} + \hat{Z}_t \quad (97)$$

$$\hat{Z}_t = \rho \hat{Z}_{t-1} + \tilde{e}_t \quad , \quad \rho \in [0, 1) \quad , \quad \tilde{e}_t \sim N(0, 1) \quad (98)$$

## 5 Calibration and Aggregate Dynamic Behavior

The model parameters are calibrated such that the time elapsing between the beginning of period  $t$  until the initiation of period  $t + 1$  is one quarter. We mostly adopt the values widely found in the literature (see for instance Smets and Wouters (2006) or Casares (2006)), but considering that our Phillips curves are structurally different than usual. In order to resemble an annual steady state real interest rate of four percent, we equalize the discount factor  $\beta$  to the value of 0.99. The structural parameters of household utility are set such that the pertinent elasticities are given by  $1/\sigma = 1/2$ ,  $1/\nu = 1/4$ , and  $1/\eta = 1/2$ . If internal habit formation is assumed to be at work, the corresponding parameter is set as  $h = 0.85$ , which is in line to Casares (2006). We impose an output share of labor  $\alpha = 0.3$ . The substitution elasticities are fixed as  $\epsilon_p = 11$ ,  $\epsilon_w = 6$ , and  $\zeta = 3.5$ . This implies steady state markups on firms' and households' marginal cost of 10 and 20 percent respectively whereas banks add 40 percent on  $R^M$ . We impose an adjustment cost rigidity parameter  $\psi_p$  that resembles the probability of price non-adjustment  $\theta_p$  under the staggered pricing assumption of Calvo (1983). The rule-of-thumb behavior is formulated in the version of Galí, Gertler, and López-Salido (2001). In this setting, we obtain the corresponding hybrid New Keynesian Phillips curve for price inflation:

$$\hat{\pi}_t^p = \gamma_1^c \hat{\pi}_{t-1}^p + \gamma_2^c E_t [\hat{\pi}_{t+1}^p] - \gamma_3^c E_t [\hat{\pi}_{t+2}^p] + \gamma_4^c \widehat{MC}_t \quad (99)$$

where the superscript 'c' denotes reaction parameters under the Calvo pricing assumption.

These are given by:

$$\gamma_1^c = \frac{[1 + \alpha (\epsilon_p (1 - \beta \theta_p) - 1)] \omega_p}{[1 + \alpha (\epsilon_p (1 - \beta \theta_p) - 1)] (\theta_p + \omega_p (1 - \theta_p)) + (1 - \alpha) \beta \theta_p \omega_p} \quad (100)$$

$$\gamma_2^c = \frac{(1 - \alpha) \beta \theta_p}{[1 + \alpha (\epsilon_p (1 - \beta \theta_p) - 1)] (\theta_p + \omega_p (1 - \theta_p)) + (1 - \alpha) \beta \theta_p \omega_p} \quad (101)$$

$$\gamma_3^c = 0 \quad (102)$$

$$\gamma_4^c = \frac{(1 - \alpha) (1 - \beta \theta_p) (1 - \theta_p) (1 - \omega_p)}{[1 + \alpha (\epsilon_p (1 - \beta \theta_p) - 1)] (\theta_p + \omega_p (1 - \theta_p)) + (1 - \alpha) \beta \theta_p \omega_p} \quad (103)$$

The parameter  $\omega_p$  denotes the fraction of firms indexing its price to the last-periods inflation rate (following a ‘rule-of-thumb’). In order to compute  $\psi_p$ , we induce the purely forward-looking Phillips curves ( $\omega_p = \nu_p = 0$ ) and equalize the current inflation rates  $\hat{\pi}_t^p$ . This pins  $\psi_p$  down against  $\theta_p$ :

$$\psi_p = \frac{\theta_p [1 + \alpha (\epsilon_p - 1)] Y \epsilon_p}{(1 - \theta_p) (1 - \beta \theta_p) (1 - \alpha) \mu_p} \quad (104)$$

Concerning our adjustment cost specification (13), the only parameter to be still calibrated is  $\nu_p$ . We leave it unassigned at first in order to visualize inflation persistence implications across its different values. We proceed in a similar way concerning the nominal wage rigidity parameter  $\psi_w$ . That is, we derive the New Keynesian Phillips curve under the staggered nominal wage setting and compute the pertinent forward looking equations. Nominal wage inflation evolution á la Calvo (1983) can be shown to be:

$$\hat{\pi}_t^w = \kappa_1^c \hat{\pi}_{t-1}^w + \kappa_2^c E_t [\hat{\pi}_{t+1}^w] - \kappa_3^c E_t [\hat{\pi}_{t+2}^w] + \kappa_4^c (\overline{MRS}_t - (\hat{W}_t - P_t)) \quad (105)$$

where the corresponding composite parameters are given by:

$$\kappa_1^c = \frac{\theta_w \omega_w}{\theta_w (1 - \omega_w (1 + \beta (\theta_w)^2)) + \omega_w} \quad (106)$$



$$\kappa_2^c = \frac{\beta \theta_w}{\theta_w (1 - \omega_w (1 + \beta (\theta_w)^2)) + \omega_w} \quad (107)$$

$$\kappa_3^c = 0 \quad (108)$$

$$\kappa_4^c = \frac{(1 - \theta_w) (1 - \omega_w) (1 - \beta \theta_w)}{[\theta_w (1 - \omega_w (1 + \beta (\theta_w)^2)) + \omega_w] (1 + \eta \epsilon_w)} \quad (109)$$

$$\kappa_5^c = \frac{\beta \theta_w (1 - \theta_w) \omega_w}{\theta_w (1 - \omega_w (1 + \beta (\theta_w)^2)) + \omega_w} \quad (110)$$

Again,  $\theta_w$  is the constant probability that a household does not adjust its nominal wage under the Calvo setting and  $\omega_w$  gives the fraction of households setting its wage as a price inflation markup over their last period's nominal wage. Note that the price inflation term described by  $\kappa_5^c$  is not present in our specification but is a specific result of the Calvo wage setting environment. However, the forward-looking wage inflation schedule ( $\omega_w = 0$ ) implies  $\kappa_1^c = \kappa_5^c = 0$ . Letting  $\nu_w = 0$  in our specification (66) and equalizing  $\hat{\pi}_t^w$  of both wage inflation Phillips curves pins down the parameter value of  $\psi_w$  as the counterpart of  $\theta_w$ :

$$\psi_w = \frac{\theta_w (1 + \epsilon_w \eta) (\epsilon_w - 1) (W/P) N}{(1 - \beta \theta_w) (1 - \theta_w)} \quad (111)$$

We proceed in exactly the same way with the loan rate equation (77). Its staggered counterpart with the non-adjustment probability  $\tau$  can be calculated as:

$$\hat{R}_t^L = \varphi_1^c \hat{R}_{t-1}^L - \varphi_2^c \hat{R}_{t-2}^L + \varphi_3^c E_t [\hat{R}_{t+1}^L] - \varphi_4^c E_t [\hat{R}_{t+2}^L] + \varphi_5^c \hat{R}_t^M \quad (112)$$

$$\varphi_1^c = \frac{\tau}{1 + \beta \tau^2} \quad (113) \quad \varphi_2^c = 0 \quad (114)$$

$$\varphi_3^c = \frac{\beta \tau}{1 + \beta \tau^2} \quad (115) \quad \varphi_4^c = 0 \quad (116)$$

$$\varphi_5^c = \frac{(1 - \tau)(1 - \beta\tau)}{1 + \beta\tau^2} \quad (117)$$

where we already have set a potential indexing parameter ‘ $\omega_r$ ’ equal to zero. This is in line with the modelling strategy pursued by Hülsewig, et al. (2009), who do not impose a backward-looking feature in the change of loan rates because such an endogeneity is not observed in the data. Assuming  $v_r = 0$  in our loan rate relationship (77) and proceeding as done so far, we arrive at:

$$\psi_r = \frac{\tau\zeta(W/P)NR^M}{1 + \tau[\beta(\tau - 1) - 1]} \quad (118)$$

We first generate the very basic version of the New Keynesian model under price adjustment costs, where the probability of price non-adjustment  $\theta_p$  is standardly assigned a quarterly value of 0.75. That is, we shut down any potential sources of persistence in the model itself. For example, setting  $\theta_w = 0$  prevents the real wage  $W_t/P_t$  to behave in a predetermined way. We simulate in the first step a one-off increase of the interest instrument rate ( $\rho = 0$ ). This enables us to isolate the time series effects stemming from the novel parameter  $v_p$  across values ranging from 0 to 15000. In a second step, we assume a highly persistent one percent shock impulse ( $\rho = 0.8$ ) and undertake the same experiment concerning  $v_p$ . An overview of the baseline calibration is given by table 1<sup>5</sup>. Table 2 gives autocorrelation coefficients of the shock variable, real output and price inflation after a one percent positive shock impulse. A parameter  $\rho = 0$  means that there is no autocorrelation in the shock process of  $\hat{Z}_t$ . The shock impulse to the instrument rate  $\hat{R}_t$  is therefore completely reverted at the end of the shock period. Further, since we shut down internal habit formation in consumption  $h = 0$ , the freedom of autocorrelation is directly translated to real output. However, the same conclusion applies for price inflation only if  $v_p$  equals to zero. According to table 2, a positive level of this parameter (here

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<sup>5</sup> See the list of tables and figures below.

$v_p = 200$ ) introduces a meaningful degree of price inflation persistence up to the last three periods in the absence of any other persistence source. In other words,  $v_p > 0$  generates endogenous price inflation persistence. The impulse responses of price inflation in figure 1 corroborate this fact and show typical properties of inflation endogeneity, namely a damped jump decrease in the shock period followed by a longer-lasting reversal to its steady state. The figure also suggests that an increasing level of  $v_p$  accentuates the persistence effects. Note that identical implications apply for  $v_w$  concerning wage inflation. A positive value of  $v_w$  generates similar persistence effects on  $\hat{\pi}_t^w$ , even if the underlying shock impulse is not autocorrelated. The same reasoning applies for any other nominal variable under purely nominal frictions, as for example the loan rate  $\hat{R}_t^L$ .

We proceed to investigate the consequences of long-lasting shocks ( $\rho = 0.8$ ) in the baseline calibration. If we set  $v_p$  equal to zero, the only source of persistence stems from the autoregressive shock process of  $Z_t$ . Following table 3, output and price inflation (as well as all other model variables) show the same degree of autocorrelation as the shock process. This is the main weakness of the standard (baseline) New Keynesian model because empirical impulse responses show a considerably damped response when the shock occurs and an amplified development of nominal and real variables in the following periods. However, if we induce price inflation endogeneity ( $v_p = 200 > 0$ ), the model displays desirable characteristics that are known from macroeconomic stylized facts. As visible in table 3, price inflation autocorrelation increases by 0.2 points, but also at the cost of output persistence in the same amount. Regardless, the latter could be restored through  $h > 0$  leaving the advantage of a positive parameter  $v_p$  intact. Most convincingly, the impulse responses of price inflation in figure 2 show the distinctive hump shape widely observed in the empirical macroeconomic literature. It should become clear that with an increasing degree of price inflation endogeneity (i.e. an increasing  $v_p$ ) the hump shape accentuates. In summary, two ingredients are needed in order to generate empirical responses in our model: a highly persistent autoregressive shock process and a model-innate persistence source. In contrast to existing literature, our inflation endogeneity stems solely from nominal rigidities instead of real frictions.

The computational results shown so far underline the potential ability of our adjustment cost specification to generate inflation persistence. In the following, we pursue a direct comparison with the widely applied Calvo pricing specification with rule-of-thumb setters. The Calvo setting is taken as a point of reference because researchers in this area have a common sense of its implications. Therefore, we have two model versions differing only in their inflation curves. These are given in the Calvo setting by (99), (105), and (112), while for the adjustment cost setting the pertinent equations are (59), (66), and (77). So far our calibration was targeted at the isolated implications of our rigidity modeling. From now on, we calibrate the model parameters in order to obtain impulse responses observed in empirical studies. Accordingly, we let all rigidities and persistence sources be present in the model economy. An overview of the implied reaction parameters is given by table 4. We let the rigidity parameters be characterized by  $\theta_w = 0.61$ ,  $\tau = 0.41$ ,  $\omega_p = 0.71$ , and  $\omega_w = 0.38$  as estimated in Hülsewig et al. (2009). Further, we induce internal habit formation in consumption by setting  $h = 0.85$  (Casares (2006)) and assume a highly persistent shock process ( $\rho = 0.8$ ). Moreover, the central bank smoothes interest rate movements ( $\phi = 0.85$ ) over time. Although our inflation curves are structurally different due to additional expectation terms, the novel rigidity parameters are set to reproduce the impulse responses of the Calvo setting as close as possible. We find that this is the case for relatively high values, namely  $v_p = 5000$  and  $v_w = 5000$ . Since Hülsewig et al. (2009) do not model the change of the loan rate as backward-looking, we induce the equivalent equation in (77) by setting  $v_r = 0$ . We simulate again a persistent percentage point increase of the instrument interest rate  $\hat{R}_t$ . Table 5 gives descriptive statistics of core variables under the two model specifications. A first result standing out is the highly increased volatility of price inflation and the relatively low variability of wage inflation in the adjustment cost model. However, the remaining variables display fairly similar second moments. These results are translated into the corresponding impulse responses. Figure 3 shows an accentuated hump-shape of price inflation while nominal wage inflation reverts to its steady state smoothly and only from below. Accordingly to their second moments in table 5, real output, employment, and interest rates show similar

adjustment paths as in the Calvo setting. Note further, that our adjustment cost structure generates nearly the same contemporaneous correlation coefficients with respect to real output. However, the link between nominal wage inflation and real output is much stronger in our approach. The quantitative differences between the two rigidity models are traced back to their structural differences when considering backward-looking elements directly linked to additional expectational terms. Nevertheless, the appearance of a price inflation rate term two periods ahead does not counteract the qualitative implications of the Calvo model.

## 6 Conclusions

The non-neutrality of monetary policy is usually achieved through the assumption of staggered price setting decisions at the agent level (Calvo (1983)). Equivalent real effects are obtained by the existence of menu costs commonly postulated in the tradition of Rotemberg (1982) and Hairault and Portier (1993). However, none of these adaptations is able to generate the amplified inflation persistence observed in empirical data. The introduction of inflation inertia under the Calvo setting requires a rule-of-thumb behavior which represents a purely nominal rigidity at the individual level. In contrast, the adjustment cost environment usually requires additional frictions in the real sector such as real wage contracting or input adjustment rigidities. We show that inflation inertia could be well traced back to purely nominal rigidities. For this purpose, we undertake a slight alteration of the real adjustment cost structure suggested by Hairault and Portier (1993). The main result of this respecification is the appearance of a backward-looking inflation term, which is directly linked to a further expectational expression. The latter comprises inflation expectations two periods ahead. We find that this is a general result when attempting to generate a backward term in the inflation schedule that is due to nominal rigidities only. While the inclusion of such a term is a striking feature in order to amplify persistence, the additional expectations tend to enforce inertia and to increase inflation volatility. Consequently, the intended analogy to the Calvo setting with respect to purely nominal frictions leads to structurally more sophisticated Phillips curves with particular quantitative implications. Nevertheless, the qualitative responses of model variables remain close to those implied by the Calvo environment since they share similar hump-shaped responses. A fruitful area of research would be to assess the empirical value of the novel rigidity coefficients introduced here. As these parameters determine the backward component of inflation relationships, they must display a significant value on the grounds of empirical data. At the same time, they would highlight the empirical magnitude of two period-ahead rational expectations.

## A Tables

**Table 1:** Structural and composite parameter values in the baseline calibration under adjustment cost-driven nominal frictions. ‘t.b.c.’=‘to be calibrated’.

|            |            |             |                          |                     |                       |                      |                      |
|------------|------------|-------------|--------------------------|---------------------|-----------------------|----------------------|----------------------|
| $\alpha$   | $\beta$    | $\sigma$    | $\eta$                   | $\nu$               | $\epsilon_p$          | $\epsilon_w$         | $\zeta$              |
| 0.3        | 0.99       | 2           | 2                        | 4                   | 11<br>( $\mu_p=1.1$ ) | 6<br>( $\mu_w=1.2$ ) | 3.5<br>( $\Xi=1.4$ ) |
|            |            |             | $\theta_p$               | $\theta_w$          | $\tau$                |                      |                      |
|            |            |             | 0.75<br>( $\psi_p=553$ ) | 0<br>( $\psi_w=0$ ) | 0<br>( $\psi_r=0$ )   |                      |                      |
| $\gamma_1$ | $\gamma_2$ | $\gamma_3$  | $\gamma_4$               | $\kappa_1$          | $\kappa_2$            | $\kappa_3$           | $\kappa_4$           |
| 0          | 1          | 0           | 0.015                    | 0                   | 1                     | 0                    | 769                  |
|            |            | $\varphi_1$ | $\varphi_2$              | $\varphi_3$         | $\varphi_4$           | $\varphi_5$          |                      |
|            |            | 0           | 0                        | 0                   | 0                     | 1                    |                      |
| $\Theta_1$ | $\Theta_2$ | $\Theta_3$  | $\Theta_4$               | $\Phi_1$            | $\Phi_2$              | $\Phi_3$             | $\Phi_4$             |
| 0          | 1          | 0           | 0.5                      | 0.5                 | 0                     | 0                    | 24.75                |
| $\iota_1$  | $\iota_2$  | $\iota_3$   | $\delta_\pi$             | $\delta_y$          | $\phi$                | $h$                  | $\rho$               |
| 2          | 0          | 0           | 1.5                      | 0.5                 | 0                     | 0                    | 0 (or<br>0.8)        |
|            |            | $R^M$       | $v_p$                    | $v_w$               | $v_r$                 |                      |                      |
|            |            | 1.01        | t.b.c.                   | 0                   | 0                     |                      |                      |

**Table 2:** Autocorrelation of simulated core variables in the baseline calibration after a one-off shock impulse ( $\rho = 0$ ) under  $v_p = 0$ . Entries enclosed by [...] have been generated under  $v_p = 200$ .

| Period          | $t - 1$     | $t - 2$     | $t - 3$     | $t - 4$  | $t - 5$  |
|-----------------|-------------|-------------|-------------|----------|----------|
| $\hat{Y}_t$     | 0<br>[0]    | 0<br>[0]    | 0<br>[0]    | 0<br>[0] | 0<br>[0] |
| $\hat{\pi}_t^p$ | 0<br>[0.22] | 0<br>[0.05] | 0<br>[0.01] | 0<br>[0] | 0<br>[0] |
| $\hat{Z}_t$     | 0<br>[0]    | 0<br>[0]    | 0<br>[0]    | 0<br>[0] | 0<br>[0] |

**Table 3:** Autocorrelation of simulated core variables in the baseline calibration after a persistent shock impulse ( $\rho = 0.8$ ) under  $v_p = 0$ . Entries enclosed by [...] have been generated under  $v_p = 200$ .

| Period          | $t - 1$       | $t - 2$        | $t - 3$        | $t - 4$        | $t - 5$        |
|-----------------|---------------|----------------|----------------|----------------|----------------|
| $\hat{Y}_t$     | 0.8<br>[0.93] | 0.90<br>[0.87] | 0.86<br>[0.83] | 0.81<br>[0.79] | 0.77<br>[0.75] |
| $\hat{\pi}_t^p$ | 0.8<br>[0.97] | 0.90<br>[0.92] | 0.86<br>[0.88] | 0.81<br>[0.83] | 0.77<br>[0.79] |
| $\hat{Z}_t$     | 0.8<br>[0.8]  | 0.90<br>[0.90] | 0.86<br>[0.86] | 0.81<br>[0.81] | 0.77<br>[0.77] |



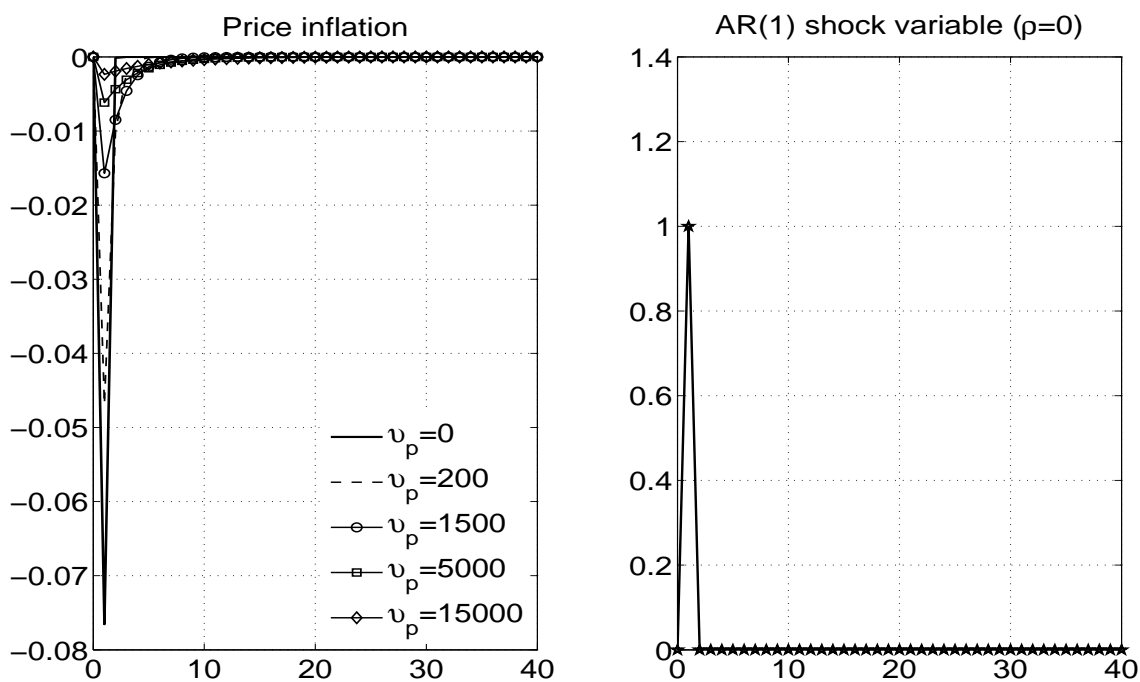
**Table 4:** Structural and composite parameter values in the full-scale calibration under adjustment cost- and ruler-of-thumb-driven nominal frictions.

|              |              |                             |                            |                           |                       |                      |                      |
|--------------|--------------|-----------------------------|----------------------------|---------------------------|-----------------------|----------------------|----------------------|
| $\alpha$     | $\beta$      | $\sigma$                    | $\eta$                     | $\nu$                     | $\epsilon_p$          | $\epsilon_w$         | $\zeta$              |
| 0.3          | 0.99         | 2                           | 2                          | 4                         | 11<br>( $\mu_p=1.1$ ) | 6<br>( $\mu_w=1.2$ ) | 3.5<br>( $\Xi=1.4$ ) |
|              |              | $\theta_p$                  | $\theta_w$                 | $\tau$                    | $\omega_p$            | $\omega_w$           |                      |
|              |              | 0.75<br>( $\psi_p=800.06$ ) | 0.61<br>( $\psi_w=75.65$ ) | 0.41<br>( $\psi_r=1.22$ ) | 0.85                  | 0.61                 |                      |
| $\gamma_1$   | $\gamma_2$   | $\gamma_3$                  | $\gamma_4$                 | $\kappa_1$                | $\kappa_2$            | $\kappa_3$           | $\kappa_4$           |
| 0.32         | 1            | 0.31                        | $\approx 0$                | 0.33                      | 1                     | 0.32                 | $\approx 0$          |
| $\gamma_1^c$ | $\gamma_2^c$ | $\gamma_3^c$                | $\gamma_4^c$               | $\kappa_1^c$              | $\kappa_2^c$          | $\kappa_3^c$         | $\kappa_4^c$         |
| 0.61         | 0.29         | 0                           | 0.0072                     | 0.34                      | 0.90                  | 0                    | 0.0062               |
|              |              | $\varphi_1$                 | $\varphi_2$                | $\varphi_3$               | $\varphi_4$           | $\varphi_5$          |                      |
|              |              | 0.35                        | 0                          | 0.35                      | 0                     | 0.30                 |                      |
|              |              | $\varphi_1^c$               | $\varphi_2^c$              | $\varphi_3^c$             | $\varphi_4^c$         | $\varphi_5^c$        |                      |
|              |              | 0.35                        | 0                          | 0.35                      | 0                     | 0.30                 |                      |
| $\Theta_1$   | $\Theta_2$   | $\Theta_3$                  | $\Theta_4$                 | $\Phi_1$                  | $\Phi_2$              | $\Phi_3$             | $\Phi_4$             |
| 0.33         | 1            | 0.33                        | 0.0046                     | 36.07                     | 17.88                 | 17.70                | 24.75                |
| $l_1$        | $l_2$        | $l_3$                       | $\delta_\pi$               | $\delta_y$                | $\phi$                | $h$                  | $\rho$               |
| 144.29       | 71.50        | 70.79                       | 1.5                        | 0.5                       | 0.85                  | 0.85                 | 0.8                  |
|              |              | $R^M$                       | $v_p$                      | $v_w$                     | $v_r$                 |                      |                      |
|              |              | 1.01                        | 5000                       | 5000                      | 0                     |                      |                      |

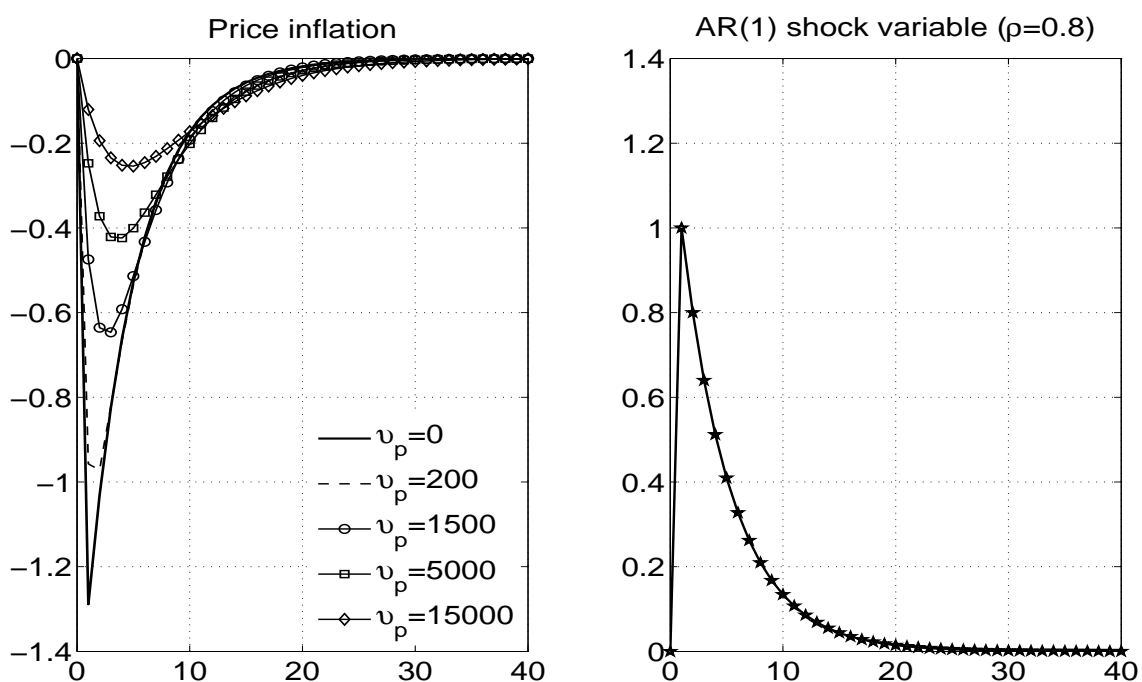
**Table 5:** Descriptive statistics of simulated core variables in the full-scale calibration.

| Variable                           | $\hat{Y}$ | $\hat{\pi}^p$ | $\hat{\pi}^w$ | $\hat{R}^M$ | $\hat{R}^L$ | $\hat{N}$ |
|------------------------------------|-----------|---------------|---------------|-------------|-------------|-----------|
| <u>(a) Standard deviation (%)</u>  |           |               |               |             |             |           |
| Adjustment costs                   | 6.45      | 0.86          | 1.12          | 4.43        | 4.12        | 9.21      |
| Rule-of-thumb pricing              | 6.76      | 0.43          | 2.32          | 4.66        | 4.35        | 9.65      |
| <u>(b) Correlation with output</u> |           |               |               |             |             |           |
| Adjustment costs                   | 1         | 0.8           | 1             | -0.94       | -0.96       | 1         |
| Rule-of-thumb pricing              | 1         | 0.98          | 0.11          | -0.95       | -0.96       | 1         |

## B Figures



**Figure 1:** Impulse responses of annualized price inflation in the baseline model after a one percent one-off increase of the instrument interest rate across different values of the rigidity parameter  $v_p$ .



**Figure 2:** Impulse responses of annualized price inflation in the baseline model after a one percent persistent increase of the instrument interest rate across different values of the rigidity parameter  $\nu_p$ .



**Figure 3:** Impulse responses of core variables after a one percent increase of the instrument interest rate under the adjustment cost-extended and the staggered pricing model.

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