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Accounting for inflation dynamic in a fully optimizing macroeconomic framework: evidence from the US states

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ABSTRACT
This article proposes a New Keynesian DSGE model that can capture the hump-shaped response of inflation to a monetary policy shock that does not depend upon backward-looking elements for the price and wage-setting, such as the indexation of wages or prices. The two additional elements required to achieve a hump-shaped response are roundabout production structure (input–output structure for production) and working capital. Depending on the model's parameterization, this channel can provide a pronounced response of inflation. In addition, our article provides some reduced-form evidence about the hump-shaped response of inflation using a VAR with Cholesky ordering.

KEYWORDS
Endogenous propagation; inflation persistence problem; new Keynesian DSGE model; roundabout production structure; working capital

JEL CLASSIFICATION
E32; E62

1. Introduction

Inflation has returned after years of hiding in the shadows. It is rising everywhere, afflicting all economies, including wealthy ones like the United States (US). Inflation accelerated in January in the US to its highest level since 1982, driving prices up at a 7.5% annual rate. Furthermore, key factors in the US indicate possible future increases in inflation rates. Thus, accurate modelling of inflation dynamics remains essential. Our article undertakes the important agenda of building theory-consistent models that account for some salient features of inflation.

Most empirical studies examining post-war data from the US show that post-war inflation is characterized by highly serially correlated movements (Fuhrer and Moore 1995; Nelson 1998; Pivetta and Reis 2007; Kurozumi and Zandweghe 2019) and that monetary shocks generate an empirical inflation response that is persistent and hump shaped. Identifying a theory that can successfully explain the US inflation dynamic while being entirely consistent with the optimal behaviours of firms and households has been a tremendous challenge facing macroeconomists for nearly two decades. Over the years, a vast literature[1] has emerged in reaction to important anomalies plaguing the canonical New Keynesian Phillips Curve NKPC) model with sticky prices, including a weak inflation persistence as opposed to the high serial correlation of inflation observed during the post-war period (Fuhrer and Moore 1995; Gordon 1997; Nelson 1998; Pivetta and Reis 2007) and a sharp and monotonically declining response of inflation in the wake of a positive aggregate demand shock unlike a modest, hump-shaped response (Mankiw 2001; Mankiw and Reis 2002; Walsh 2005).

One class of models has assumed short-run deviations from the optimal behaviours of wage-setting households and price-setting firms to address these anomalies. For instance, in (Galí and Gertler (1999,) a fraction of firms adopts rule-of-thumb price-setting behaviour linking current price changes to past inflation. In Christiano, Eichenbaum, and Evans (2005), nominal prices and wages not reoptimized in a given period are fully indexed to the last period's inflation rate. In Smets and Wouters (2007), the Calvo model in both price and wage settings is augmented by assuming that prices that are not readjusted are partially indexed to past inflation rates. These assumptions add the one-period lagged

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[1]Prominent examples of this class of models include Yun (1996); Rotemberg (1996); Ireland (1997); Christiano, Eichenbaum, and Evans (1999); Christiano, Eichenbaum, and Evans (2005); and Cogley and Sbordone (2008).

inflation rate to the NKPC, helping the new Keynesian model better track inflation dynamics. However, backwards-looking price-setting and wage-setting mechanisms have been severely criticized both on theoretical and empirical grounds (Woodford 2007; Christiano, Eichenbaum, and Trabandt 2016). The criticisms addressed to indexation are of two kinds. One is the lack of a solid microeconomic foundation in backwards-looking price and wage mechanisms. (Cogley and Sbordone 2008). Another criticism is that once included in a Calvo-framework indexation counterfactually implies that all prices and wages adjust every 3 months, which contradicts microeconomic evidence on the adjustments frequency of price and wage (e.g., see. Chari, Kehoe, and McGrattan 2009; Barattieri, Basu, and Gottschalk 2014).

Focusing on short-run inflation dynamics, several recent papers have argued that inflation persistence can be explained without backwards-looking components by modelling trend inflation as a driftless random walk process (Sbordone 2007; Cogley and Sbordone 2008), presumably linked to shifts in the Federal Reserve's long-run inflation target (Ireland 2007). Questioning the economic rationale behind random walk models of trend inflation and monetary policy, West (2007) concludes that these developments fall 'in the camp that relies on exogenous rather than intrinsic sources of inertia'. Still, another line of research focuses on positive trend inflation as a source of inflation and output persistence in new Keynesian Phillips curve NKPC) models (Ascari 2004; Ascari and Ropele 2007; Shirota 2015; Kurozumi and Zandweghe 2019)

Our article explores a different approach. It suggests a Dynamic Stochastic General Equilibrium (DSGE) model that can potentially explain inflation dynamics in the aftermath of a monetary policy shock. In our model, the optimal decisions made by firms and households, including price and wage setting, are totally derived from explicit individual optimization problems. The model includes Calvo's (1983) nominal contracts and real adjustment frictions, such as consumer habit formation, variable capital utilization, and investment adjustment costs, which are now standard features in DSGE models. Nominal interest rates are set following a Taylor-type rule wherein the central bank smooths movements in nominal interest rates while systematically responding to deviations of inflation and output growth from targets.

Our model differs in various ways from recent small-scale new-Keynesian business cycle models. First, our model precludes the use of ad hoc backwards-looking components in the NKPC and slow-moving trend inflation to keep our focus on a fully optimizing framework. Second, we assume that firms not only use capital services and labour to produce goods but also intermediate inputs in a so-called 'roundabout' production structure. Basu (1995) states that all firms use intermediate inputs to produce in an input–output production structure. The 'roundabout' production structure is intended to capture the growing interdependence of goods produced in modern industrialized economies. Indeed, Hanes (1999) and Huang, Liu, and Phaneuf (2004) support that the degree of roundaboutness in US goods produced has significantly increased from the interwar to the post-war era. Furthermore, Basu (1995) argues that US Input–Output Tables strongly support a 'roundabout' rather than an 'in-line' view of production. This author showed that the interaction between intermediate goods and state-dependent price rigidity at the firm level can act as a multiplier for price stickiness that amplifies the economy-wide degree of price rigidity. Third, just like in Christiano, Eichenbaum, and Evans (2005), our model incorporates a working capital channel that results from our assumption that firms need to borrow money from the bank to produce since they must pay their employees before selling their goods. The presence of working capital in the DSGE models means that the nominal interest rate enters the marginal cost, so a reduction in the policy rate reduces the marginal cost and paves the way for a more muted response of inflation. This is the well-known cost channel of monetary policy. It is important to consider the working capital channel for several reasons. Ravenna and Walsh (2006) give evidence in favour of the working capital channel using instrumental variable estimates of an adapted Phillips curve, and Chowdhury, Hoffmann, and Schabert (2006) provide VAR evidence that working capital is used to pay wages in the G7 countries. There are few models where working capital finances only the wage bill. In Barth and Ramey (2002), Christiano, Trabandt, and Walentin (2011) and Brault et al. (2021), working capital is used to finance payments for all production factors. Unlike these models, ours requires no backward indexation and only a limited form of working capital to explain the dynamic response of inflation to a monetary policy shock.

The following critical question is addressed in this article. Does the New Keynesian model with sticky wages and prices, working capital, and intermediate inputs have the ability to capture the dynamic response of inflation to a monetary shock? We adopt a gradual approach to prove our main points. First, we explored the empirical performance of the benchmark model, which includes all the theoretical ingredients listed above except working capital. While delivering highly serially correlated movements of inflation at short and medium lags, the benchmark model does not predict a hump-shaped response of inflation in the aftermath of a monetary policy shock as observers like Mankiw and Reis (2002), Christiano, Eichenbaum, and Evans (2005), Walsh (2005) and Christiano, Eichenbaum, and Trabandt (2016) think it should. Second, the benchmark model's failure to capture the inflation dynamic correctly brings us to add working capital to the benchmark model. Working capital requirements are frequently included in macroeconomic models that examine the effects of monetary or financial shocks. We show that this channel helps in producing a hump-shaped response of inflation. Unlike previous new Keynesian models generating a hump-shaped response of inflation (Christiano, Eichenbaum, and Evans 2005; Walsh 2005), our model, free of ad hoc backwards-looking price and wage setting mechanisms and slow-moving trend inflation, can produce a hump-shaped and highly persistent response of inflation in the aftermath of a monetary policy shock. Furthermore, varying only slightly the parameter governing investment adjustment costs, we find that the hump-shaped response of inflation can be very pronounced. Finally, to explore the roundabout production structure's role in our model's success in reproducing the short-run inflation dynamics in the wake of a monetary policy shock, we simulated our model with the working capital channel and without the roundabout production structure. The results show that inflation's hump-shaped response is determined by the interaction between the working capital channel and the roundabout production structure.

The rest of the article is organized as follows. Section 2 presents important stylized facts about inflation. Section 3 describes our medium-scale macro model with working capital and roundabout production. Section 4 discusses the model's parameters calibration. In Section 5, we present our findings. Section 6 contains some concluding remarks.

2. Post-War inflation dynamics

2.1. Evidence from VARs

One way to assess how well the New Keynesian model replicates the stylized macroeconomic facts is to compare the model's response in the aftermath of a monetary policy shock with the response in the data. A Vector Autoregressive model (VAR) is used in the data to measure the reaction to a monetary policy shock. The benchmark VAR model used to examine the effects of a monetary shock in the United States is described in the following representation:

$$Y_t = A(L)Y_{t-1} + \mu_t \tag{1}$$

The vector Y_t consists of real GDP (Y_t), consumer prices index (p_t) and the nominal short-term interest rate (i_t). The data[2] used is quarterly, the sample is $1960 : I - 2019 : III$, and all variables are seasonally adjusted and expressed in log terms, except the interest rate. The structural shocks are identified using a standard Cholesky decomposition with ordering (output, consumer prices index, policy interest rate). This decomposition method is identical to the one employed by Christiano, Eichenbaum, and Evans (1999) and Carlstrom and Paustian (2009a). Our VAR model's appropriate lag-order is found to be of order 2 using

[2]Data used in this part are extracted from the Federal Reserve Bank of St. Louis database.

standard likelihood ratio tests. In addition, we used sequential Chow tests starting in 1990 : I to test the stability of the VAR. These tests show no instability evidence at 1% confidence level.

Figure 1 displays the VAR impulse responses of inflation and output to a 1 SD monetary policy shock ±2 SE confidence bounds. These responses show that output declines following a tightening of monetary shock, and inflation reacts in a hump-shaped manner, peaking after around 2 years. These findings confirm the results obtained by Peersman and Smets (2003) and Christiano, Eichenbaum, and Evans (2005).

2.2. Evidence on inflation persistence

Fuhrer and Moore (1995) show that inflation exhibits high to extremely high persistence over the post-war period. However, Benati (2008) contends that inflation persistence has changed over time. Indeed, a drop in inflation persistence from a high level in the 1970s to a lower one starting in the 1980s is supported by, Benati and Surico (2009), Carlstrom, Timothy, and Matthias (2009b) and Davig and Doh (2014). They explain this decline by a more aggressive monetary policy reaction to inflation and changes in shock volatility. However, using various measures,

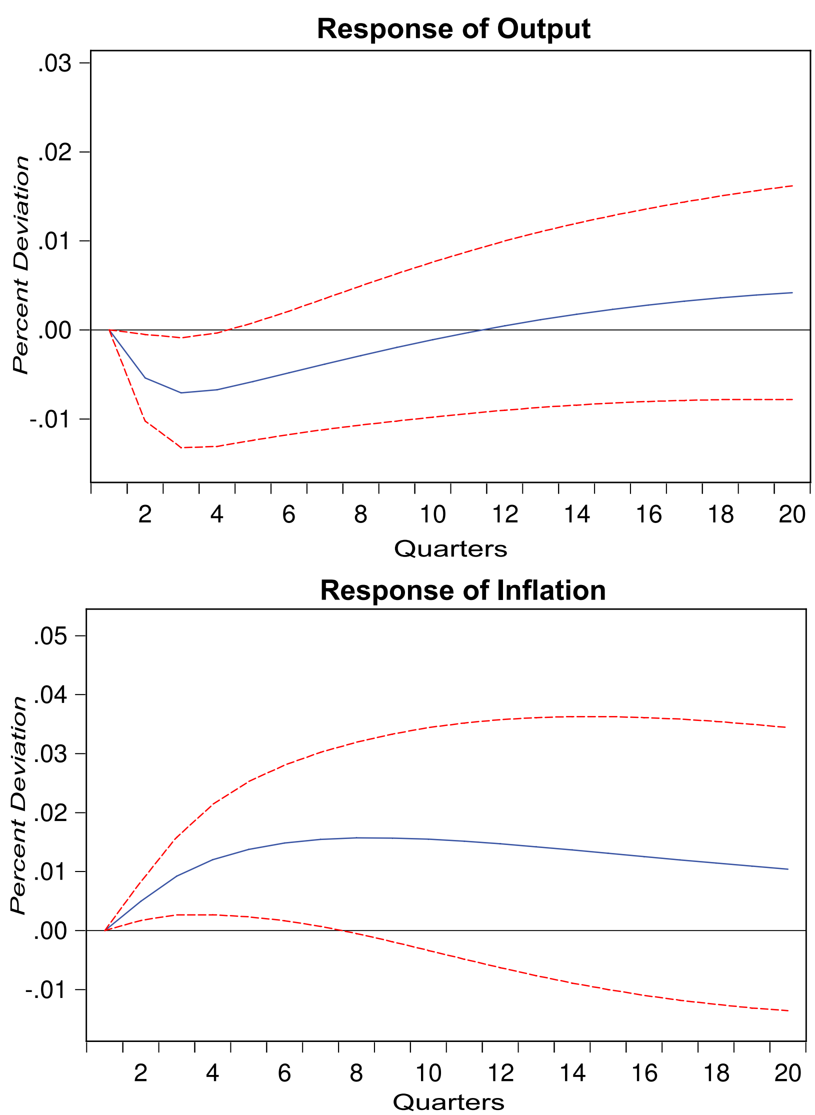

Figure 1. Responses of output and inflation to a 1 SD monetary policy shock.

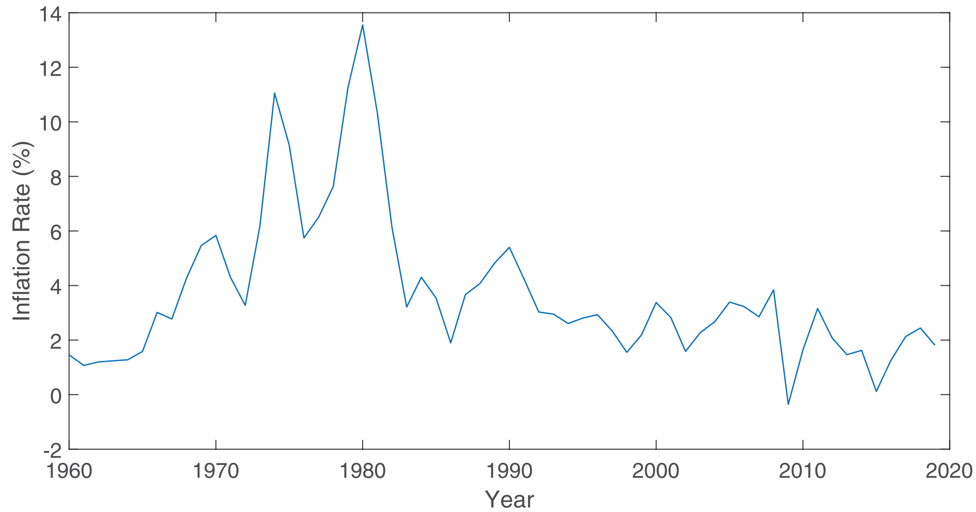

Figure 2. Post-war inflation.

Table 1. US autocorrelations of price inflation (1960:I to 2019:III).

Order of autocorrelation	1	2	3	4	5	6
Price inflation measured by the NBD	0.826	0.799	0.756	0.661	0.580	0.536
Price inflation measured by the GDPD	0.870	0.820	0.801	0.787	0.716	0.676

estimation procedures, and formal tests, Pivetta and Reis (2007) show that the persistence of US inflation has remained high and almost unchanged since 1965. Inflation persistence is often measured by summing the autoregressive coefficients obtained from the estimation of a univariate autoregressive time-series model (e.g., Fuhrer and Moore 1995; Pivetta and Reis 2007). In this empirical research, it is shown that inflation persistence is quite similar to that of a random walk.

Figure 2 shows log differences of the annually seasonally adjusted consumption prices index from 1960 to 2019. This figure shows that inflation in the US is a fairly persistent process. The inflation autocorrelation we computed supports this. The autocorrelations of the log GDP implicit price deflator (GDPD) and the log nonfarm business sector implicit price deflator (NBD) during the period 1960–2019 are shown in Table 1. The autocorrelations are high and positive at low-order lags and remain relatively high at higher-order lags.

3. The model

The economy is made up of a large number of firms, each producing a differentiated good indexed by $j \in 0,1]$; a large number of households, each endowed with a differentiated labour skill indexed by $i \in 0,1]$; and a monetary authority conducting policy according to a Taylor-type of rule. Nominal rigidities in wages and prices are modelled as Calvo-contracts.

3.1. Labour and good composites

Denoted by X_t, the composite of differentiated goods $X_t(j)$, for $j \in 0,1]$, such that $X_t = [\int_0 X_t(j)^{\frac{(\theta-1)}{\theta}} dj]^{\frac{\theta}{(\theta-1)}}$ and by L_t, the composite of differentiated labour skills $L_t(i)$, for $i \in 0,1]$, such that $L_t = [\int_0 L_t(i)^{\frac{(\sigma-1)}{\sigma}} di]^{\frac{\sigma}{(\sigma-1)}}$. $\sigma \in (1,\infty)$ is the elasticity of substitution among differentiated labour skills and $\theta \in (1,\infty)$ is the elasticity of substitution among differentiated goods. A perfectly competitive aggregate sector produces both the composite good and the composite skill.

Profit maximization yields the following demand functions for each type of skill and each type of good:

$$X_t^d(j) = \left[\frac{P_t(j)}{P_t}\right]^{-\theta} X_t, \quad (2)$$

and

$$L_t^d(i) = \left[\frac{W_t(i)}{W_t}\right]^{-\sigma} L_t. \tag{3}$$

The price and wages indexes are $P_t^{1-\theta} = \int_0 P_t(j)^{(1-\theta)} dj$ and $W_t^{1-\sigma} = \int_0 W_t(i)^{(1-\sigma)} di$, respectively.

3.2. Households

Household i'' has preferences defined over consumption and leisure:

$$E\sum_{t=0}^{\infty} \beta^t \left\{ \log(C_t(i) - bC_{t-1}(i)) - \eta \frac{L_t(i)^{1+\chi}}{1+\chi} \right\}, \tag{4}$$

The budget constraint facing household i'' at time t is

$$\begin{aligned} P_t(C_t(i) + a(Z_t(i))K_t(i) + I_t(i)) + E_t D_{t,t+1} B_{t+1}(i) \\ \leq W_t(i)L_t(i) + R_t^k Z_t(i) K_t(i) + \Pi_t(i) + B_t(i) \\ + T_t(i), \end{aligned} \tag{5}$$

where $C_t(i)$ is individual consumption, $b>0$ is the consumption habit parameter, $I_t(i)$ denotes investment, $a(Z_t(i))K_t(i)$ is the cost in units of consumption goods of setting the utilization rate of capital to $Z_t(i)$, $B_{t+1}(i)$ is household i's holdings of a nominal bond denoting a claim to one dollar in $t+1$ and costing $D_{t,t+1}$ dollars at time t, $W_t(i)L_t(i)$ is labour income, $R_t^k Z_t(i) K_t(i)$ is household i's earnings from supplying capital services, $\Pi_t(i)$ represents distributed dividends from firms, which households take as given, and $T_t(i)$ is a lump-sum transfer that the household i'' gets from the government.

The stock of physical capital $K_t(i)$ evolves according to

$$K_{t+1}(i) = (1-\delta)K_t(i) + \left[1 - S\left(\frac{I_t(i)}{I_{t-1}(i)}\right)\right] I_t(i), \tag{6}$$

where δ is the physical rate of capital depreciation. $S(.)$ is an investment adjustment cost. In line with Justiniano, Primiceri, and Tambalotti (2011), we make the assumptions that $S(1) = S'(1) = 0$, and $\kappa \equiv S''(1) > 0$, where κ denotes the investment adjustment cost parameter. The steady-state rate of capital utilization equals one, and $a(1) = 0$.

The household chooses $C_t(i), Z_t(i), I_t(i), K_{t+1}(i)$ and $B_{t+1}(i)$ for all $t = 0, 1, 2, \ldots$ to maximize its utility function (4) subject to the budget constraint (5) for all $t = 0, 1, 2, \ldots$ To derive the first-order conditions for this problem, we make the assumption that implicit state-contingent financial contracts cover each household against the idiosyncratic income risk arising from the asynchronized wage adjustments (e.g. Rotemberg and Woodford 1997; Huang, Liu, and Phaneuf 2004). With such financial arrangements, nominal wages and hours worked can vary from household to household, but equilibrium investment and consumption are the same across households. The problem's first-order conditions are as follows:

$$C_t : \lambda_t^r = \frac{1}{C_t - bC_{t-1}} - \beta b E_t\left(\frac{1}{C_{t+1} - bC_t}\right), \tag{7}$$

where $\lambda_t^r = P_t \lambda_t$;

$$Z_t : R_t^k K_t = P_t a'(Z_t) K_t, \tag{8}$$

$$\begin{aligned} I_t : -\beta^t \lambda_t P_t + \beta^t \mu_t \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right) \\ - \beta^t \mu_t S'\left(\frac{I_t}{I_{t-1}}\right) \frac{I_t}{I_{t-1}} + E_t\left(\beta^{t+1} \mu_{t+1} S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right) = 0, \end{aligned} \tag{9}$$

$$\begin{aligned} K_{t+1} : -\beta^t \mu_t \\ + E_t(\beta^{t+1} \lambda_{t+1}(R_{t+1}^k Z_{t+1} - P_{t+1} a(Z_{t+1}))) \\ + E_t(\beta^{t+1} \mu_{t+1}(1-\delta)) = 0, \end{aligned} \tag{10}$$

$$B_{t+1} : \lambda_t E_t(D_{t,t+1}) = \beta E_t(\lambda_{t+1}). \tag{11}$$

Letting $D_{t,t+1} = \frac{1}{1+i_t}$ and $\pi_t = \frac{P_t}{P_{t-1}}$, the last equation can be written as

$$\lambda_t^r = \beta E_t((1+i_t)\pi_{t+1}^{-1} \lambda_{t+1}^r).$$

3.2.1. Wage decision

Households can reset their nominal wage rates each period with probability $(1-\xi_w)$. A firm that cannot reoptimize its price keeps it unchanged from the previous period.

$$L_{t+h}(i) = \left(\frac{W_t(i)}{W_{t+h}}\right)^{-\sigma} L_{t+h}. \tag{12}$$

Once allowed to adjust its nominal wage, household i'' solves the following problem, taking aggregates as given:

$$\max_{W_t(i)} E_t\left(\sum_{h=0}^{\infty}(\beta\xi_w)^h\left(\begin{array}{c}-\frac{\eta}{1+\chi}\left(\frac{W_t(i)}{W_{t+h}}\right)^{-\sigma(1+\chi)}\\ L_{t+h}^{1+\chi}+\lambda_{t+h}\left(W_t(i)\left(\frac{W_t(i)}{W_{t+h}}\right)^{-\sigma}L_{t+h}\right)\end{array}\right)\right). \tag{13}$$

At date t, an household $''i''$ allowed to reset its wage rate will choose the following optimal reset wage:

$$W_t^*(i)^{1+\sigma\chi} = \frac{\sigma}{\sigma-1}E_t\left(\frac{\sum_{h=0}^{\infty}(\beta\xi_w)^h\eta W_{t+h}^{\sigma(1+\chi)}L_{t+h}^{1+\chi}}{\sum_{h=0}^{\infty}(\beta\xi_w)^h W_{t+h}^{\sigma}\lambda_{t+h}L_{t+h}}\right). \tag{14}$$

3.3. Intermediate producers

The composite good can be used as an intermediate production input or investment good, or as a final consumption good. In contrast, the composite skill can only be used only as an input for the production of each differentiated good. The production function for a good of type j'' is

$$X_t(j) = \begin{cases}\Gamma_t(j)^{\phi}\left[\overline{K}_t(j)^{\alpha}L_t(j)^{1-\alpha}\right]^{1-\phi} - F, & \text{if } \Gamma_t(j)^{\phi}\left[\overline{K}_t(j)^{\alpha}L_t(j)^{1-\alpha}\right]^{1-\phi} \geq F\\ 0, & \text{otherwise},\end{cases} \tag{15}$$

where $\Gamma_t(j)$ is the input of intermediate goods that comes from the gross output, $\overline{K}_t(j) = Z_t(i))K_t(i)$ denotes capital services and $L_t(j)$ represents labour hours. F is a fixed cost that is the same for all firms and guarantees that all firms' profits are zero in the steady state. The parameter $\phi \in (0,1)$ denotes the elasticity of output with regard to intermediate inputs, while the parameters $\alpha \in (0,1)$ and $(1-\alpha)$ represent the elasticities of value-added with regard to capital services and labour inputs.

3.3.1. Cost minimization

A firm j'' chooses the quantity of its inputs minimizing the following cost function:

$$\min \quad P_t\Gamma_t(j) + R_t^k\overline{K}_t + W_tL_t(j), \tag{16}$$

subject to

$$\Gamma_t(j)^{\phi}\left(\overline{K}_t(j)^{\alpha}L_t(j)^{1-\alpha}\right)^{1-\phi} - F \geq \left(\frac{P_t(j)}{P_t}\right)^{-\theta}X_t. \tag{17}$$

Solving the firm's cost-minimization problem yields the following nominal marginal cost function:

$$V_t = \overline{\phi}P_t^{\phi}\left[\left(R_t^k\right)^{\alpha}\left(W_tR_t\right)^{1-\alpha}\right]^{1-\phi}, \tag{18}$$

where $\overline{\phi}$ is a constant that depends on ϕ and α.

The real marginal cost, v_t, is therefore given by

$$v_t = \overline{\phi}\left[\left(r_t^k\right)^{\alpha}\left(w_tR_t\right)^{1-\alpha}\right]^{1-\phi}, \tag{19}$$

where $r_t^k = R_t^k/P_t$ and $w_t = W_t/P_t$. The higher ϕ is, the less sensitive real marginal cost is to variations in r_t^k and w_tR_t. If the roundabout production is not included in the model ($\phi = 0$), then the real marginal cost equation is:

$$v_t = \widetilde{\phi}\left[\left(r_t^k\right)^{\alpha}\left(w_tR_t\right)^{1-\alpha}\right], \tag{20}$$

where $\widetilde{\phi}$ is a constant that depends on α. Because $\phi = 0$, real marginal cost responds more strongly to variations in r_t^k and w_tR_t.

According to the last two expressions, roundabout production lowers the real marginal cost's sensitivity to changes in the real wage rate and the real rental on capital services by a factor of $(1-\phi)$. Since inflation is a function of the discounted expected stream of future real marginal costs, it is through this channel that roundabout production may act as a multiplier for price stickiness at the economy-wide level.

3.3.2. Profit maximization and price-setting

Firms can update their price in a period with probability $(1-\xi_p)$. Firms discount future profits by $D_{t,t+h}$. Let $V(X_{t+h}(j))$ be the total nominal cost of producing $X_{t+h}(j)$. Then, the problem is

$$\max_{P_t(j)} E_t\left(\sum_{h=0}^{\infty}\left(\xi_p\right)^h D_{t,t+h}(P_t(j)X_{t+h}(j) - V(X_{t+h}(j)))\right), \tag{21}$$

subject to

$$X_{t+h}(j) = \left(\frac{P_t(j)}{P_{t+h}}\right)^{-\theta} X_{t+h}. \tag{22}$$

Substituting (22) in (21), and then deriving the first-order condition leads to the following equation for the price of firm j'':

$$P_t^*(j) = \frac{\theta}{\theta-1}\frac{E_t\sum_{h=0}^{\infty}(\xi_p)^h D_{t,t+h}V_t(X_{t+h}(j))P_{t+h}^{\theta}X_{t+h}}{E_t\sum_{h=0}^{\infty}(\xi_p)^h D_{t,t+h}P_{t+h}^{\theta}X_{t+h}}. \quad (23)$$

Note that $D_{t,t+h} = \frac{\beta^h\lambda_{t+h}}{\lambda_t}$, so expressed in real terms it becomes $\frac{P_{t+h}D_{t,t+h}}{P_t}$. The real discount factor is therefore $\frac{\beta^h P_{t+h}\lambda_{t+h}}{P_t\lambda_t}$, and can be written as $\frac{\beta^h\lambda_{t+h}^r}{\lambda_t^r}$, where $\lambda_t^r = P_t\lambda_t$. Reset price inflation is therefore given by

$$\frac{P_t^*(j)}{P_t} = \frac{\theta}{\theta-1}\frac{E_t\sum_{h=0}^{\infty}(\xi_p\beta)^h\lambda_{t+h}^r\frac{V_t(X_{t+h}(j))}{P_{t+h}}P_{t+h}^{\theta}P_t^{-1}X_{t+h}}{E_t\sum_{h=0}^{\infty}(\xi_p\beta)^h\lambda_{t+h}^r P_{t+h}^{\theta-1}X_{t+h}}. \quad (24)$$

3.4. Monetary policy

The monetary authority sets the nominal interest rate at time t'' according to the following Taylor rule:

$$\widehat{R}_t = \rho_r\widehat{R}_{t-1} + (1-\rho_r)(\rho_\pi\widehat{\pi}_t + \rho_Y\widehat{g}_{Yt}) + \varepsilon_{r,t}, \quad (25)$$

where a hat over a variable represents the percentage deviation from its steady-state value, $g_{Yt} = \log(Y_t/Y_{t-1})$, ρ_r denotes the interest-smoothing parameter, ρ_π and ρ_Y are control parameters, and $\varepsilon_{r,t}$ follows an i.i.d. normal process, with a null mean and a finite variance (see Erceg and Levin 2003; Galí and Rabanal 2004)

4. Model calibration

We need to calibrate a number of factors, including the preference parameters b, χ and η, the capital depreciation rate δ, the subjective discount factor β, the capital utilization elasticity σ_a, the investment adjustment cost parameter κ, the elasticity of substitution between differentiated goods θ and that between differentiated labour skills σ, the technology parameters ϕ and α, the probability of price non-reoptimization ξ_p, the probability of wage non-reoptimization ξ_w, and the parameters of the monetary rule ρ_r, ρ_π, ρ_Y and σ_{ε_r}.[3] Table 2 contains the values assigned to these parameters.

The parameters β and χ are set to 0.99 and 2, respectively, which imply a steady-state annualized real interest rate of 4% and an intertemporal elasticity of labour hours of 0.5; η is such that the share of steady-state labour hours is about 1/3. The parameter governing consumption habit, b, is 0.8 (Fuhrer 2000; Boldrin, Christiano, and Fisher 2001; Khan, Phaneuf, and Victor 2020).

The parameter δ is fixed at 0.025, implying an annual capital depreciation rate of 10%. The parameter κ, which governs the investment adjustment cost, is set to 3 (Phaneuf and Victor 2021; El Omari 2017), and the capital utilization elasticity σ_a at 1.5 (Basu and Kimball 1997; Dotsey and King 2006). When profits in the steady state are zero, the parameter α reflects the proportion of payments to capital in total value-added in the National Income and Product Account (NIPA); this suggests that α is equal to 0.4 (Cooley and Prescott, 1995).

The parameter θ, which represents the elasticity of substitution between differentiated goods, often varies between 4 (Nakamura et al. 2018) and 11 (Huang, Liu, and Phaneuf 2004) in the literature. This implies that the markup of prices in the steady state lies between 1.1 and 1.33. The share of intermediate inputs, ϕ, measures the share of payments to intermediate input in total production cost. In the presence of markup pricing, this equals the product of the steady-state markup and the share

Table 2. Calibrated parameter values.

Parameter	Value	
Subjective discount factor	$\beta = 0.995$	
Preferences	$b = 0.8$,	$\chi = 2$
Technology parameters	$\phi = 0.6$,	$\alpha = 0.4$
Elasticity of substitution between differentiated goods	$\theta = 6$	
Elasticity of substitution between differentiated labour skills	$\sigma = 6$	
Capital depreciation rate	$\delta = 0.025$	
Investment adjustment cost parameter	$\kappa = 3$	
Capital utilization elasticity	$\sigma_a = 1.5$	
Probability of price non-reoptimization	$\xi_p = 2/3$	
Probability of wage non-reoptimization	$\xi_w = 2/3$	
Monetary policy parameters	$\rho_r = 0.8$,	$\rho_\pi = 1.5$
	$\rho_Y = 0.125$,	$\sigma_{\in_r} = 0.004$

[3]Since equilibrium dynamics are unaffected by the utility function's parameter η in the log-linearized equilibrium system, no specific value is given to it.

of intermediate input in gross output or revenue share. Therefore, ϕ is related to markup pricing and θ. More precisely, ϕ decreases with θ for a given revenue share of intermediate input. Huang, Liu, and Phaneuf (2004) rely on two data sources to assess the revenue share of intermediate input. One source is a study by Jorgenson, Frank, and Barbara (1987), which suggests that over the period $1947-1979$, the revenue share of intermediate input in total manufacturing output was 50% or more. Based on this source and a price markup between 1.1 and 1.33, ϕ varies between 0.55 and 0.67. The other source is the 1997 Benchmark Input–Output Tables of the Bureau of Economic Analysis showing that the ratio of"total intermediate" to"total industry output" in the manufacturing sector was 0.68. This would imply ϕ ranges between 0.748 and 0.90. Nakamura and Steinsson (2010) provide arguments in favour of $\phi = 0.7$. Given our admissible values of θ, this would imply that ϕ is in the range between 0.57 and 0.69. We adopt a conservative stand and set $\theta = 6$ and $\phi = 0.6$. We similarly fix the elasticity of substitution between differentiated labour skills, σ, at 6 (Huang and Liu 2002; Christiano, Eichenbaum, and Evans 2005).

The parameter representing the probability that a firm will not adjust its price (ξ_p) was set in accordance with. Coibion, Gorodnichenko, and Wieland (2012). That is, ξ_p is fixed at 0.55, allowing firms to adjust prices on average every 6.7 months. This is roughly in the middle of the empirical findings of Bils and Klenow (2004), who suggest that firms adjust their prices every four to eleven months. The parameter ξ_w, which represents the probability of wage non-reoptimization, is fixed at $2/3$, allowing households to reset nominal wages on average once every nine months. Christiano, Eichenbaum, and Evans (2005) report an estimate for this parameter of 0.64. In their 2014 study, Barattieri, Basu, and Gottschalk examined microdata for the American economy. They suggest that the average quarterly probability of a wage adjustment is between 0.211 and 0.266, which implies a degree value of nominal wage stickiness between $0.75-0.80$. In comparison to the micro estimates in Barattieri, Basu, and Gottschalk (2014), our calibration of this parameter is somewhat conservative, but it is consistent with the estimates found by Christiano, Eichenbaum, and Evans (2005).

Finally, the values assigned to Taylor rule's parameters are: $\rho_r = 0.8$, $\rho_\pi = 1.5$, and $\rho_Y = 0.125$. These values were used by Galí and Rabanal (2004) and Christiano, Eichenbaum, and Evans (2005). The monetary policy shock's SD σ_r is fixed at 0.003. This calibration is very standard in the literature.

5. Results

5.1. Short-run inflation dynamics

The benchmark model includes a roundabout production structure, a Taylor-type monetary rule, Calvo's (1983) nominal contracts and real adjustment frictions, such as consumer habit formation, variable capital utilization and investment adjustment costs. Figure 3 displays the benchmark model's main macroeconomic variables' impulse responses to a decline in the nominal interest rate. Note that our model generates a relatively small, persistent, hump-shaped response of real marginal cost to a monetary policy shock. As a result, the response of inflation to a monetary policy shock is flatter and more persistent. However, despite sluggishness, the response of inflation is not hump-shaped.

The impulse responses of real variables, such as consumption, investment, output, materials input, and hours worked are all highly persistent and hump-shaped. Note the quasi-proportionality and the similar shapes of the responses of hours worked and materials input. This benchmark model's implication is in line with the arguments in Dotsey and King (2006), who stress the importance that movements in output, labour input, and materials input at the industry and aggregate level should be approximately proportionate over the business cycle. Note also that the capital utilization response is persistent and hump-shaped, consistent with the evidence from the study by Christiano, Eichenbaum, and Evans (2005).

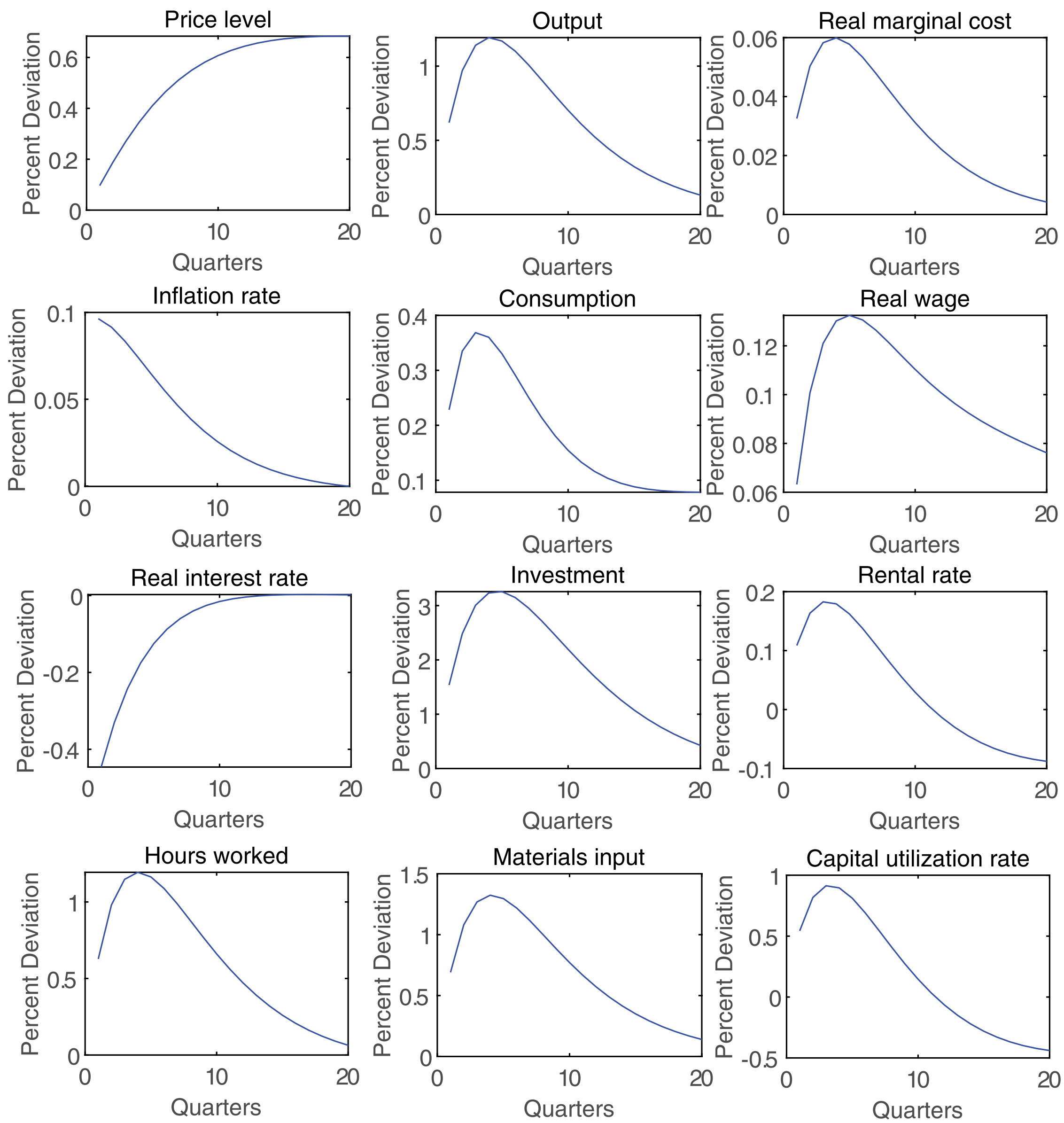

Figure 3. Impulse-responses of variables in the benchmark model.

Despite the evidence about the shape of the response of inflation in the aftermath of a monetary policy shock is scarce, several researchers have endorsed the view that a successful model should generate a persistent and hump-shaped response of inflation (Mankiw 2001; Mankiw and Reis 2002; Walsh 2005; Christiano, Eichenbaum, and Evans 2005). The results obtained in this section show that while the benchmark model predicts high persistent responses of the key macroeconomic variables, as suggested by the literature, it cannot generate a hump-shaped inflation response to a policy shock.

Christiano, Eichenbaum, and Evans (2005) address this empirical shortcoming by supposing that prices and wages that are not reoptimized in a given period are fully indexed to the last period's inflation rate. They report evidence showing that a negative shock to the nominal interest rate is followed by a decline in inflation for about six quarters and a persistent and hump-shaped rise afterwards. Since indexation results in lagged inflation being added to the New Keynesian Phillips Curve (NKPC), this assumption helps to track inflation dynamics closely. The criticisms addressed to indexation are of two kinds. One is that backwards-looking wage and price mechanisms" lack a solid microeconomic foundation" (Cogley and Sbordone 2008). Another criticism is that once included in a Calvo-framework indexation counterfactually implies that all prices and wages adjust every 3 months.

5.2. Hump-shaped response of inflation and working capital

Our objective now is to show that with few modifications, our model can generate a hump-shaped and persistent response of inflation in the aftermath of a monetary policy shock while being at the same time entirely consistent with the optimizing behaviours of firms and households. To this end, we add to the benchmark model a central element of limited participation models. That is, we suppose that firms need to borrow capital to pay their wage bill (Christiano, Eichenbaum, and Evans 1997, 2005). They borrow capital at the beginning of a period and then pay back the loan at the end at a certain gross nominal interest rate.

The cost-minimization problem becomes:

$$\min \quad P_t \Gamma_t(j) + R_t^k \overline{K}_t + W_t R_t L_t(j), \tag{26}$$

subject to Equation (17). The resulting expressions for the real marginal cost and aggregate labour hours are:

$$v_t = ((r_t^k)^\alpha (w_t R_t)^{1-\alpha})^{1-\phi}, \tag{27}$$

and

$$L_t = (1-\alpha)(1-\phi)\frac{V_t}{W_t R_t}(s_t X_t + F). \tag{28}$$

Both the real marginal cost and aggregate labour hours now depend on the gross nominal interest rate. It is clear that working capital means that the nominal interest rate enters the marginal cost, so that a reduction in the policy rate reduces the marginal cost and paves the way for a more muted response of inflation. This is the well-known cost channel of monetary policy. Figure 4 compares the response of inflation in the benchmark model and the same model augmented with working capital. This figure makes it quite evident that inflation responds in a hump-shaped pattern when working capital is considered.

We assess the capability of the benchmark model with working capital to account for inflation persistence, defined following Fuhrer and Moore (1995), as the high, positive, slowly decaying autocorrelations of inflation observed in post-war US data (see

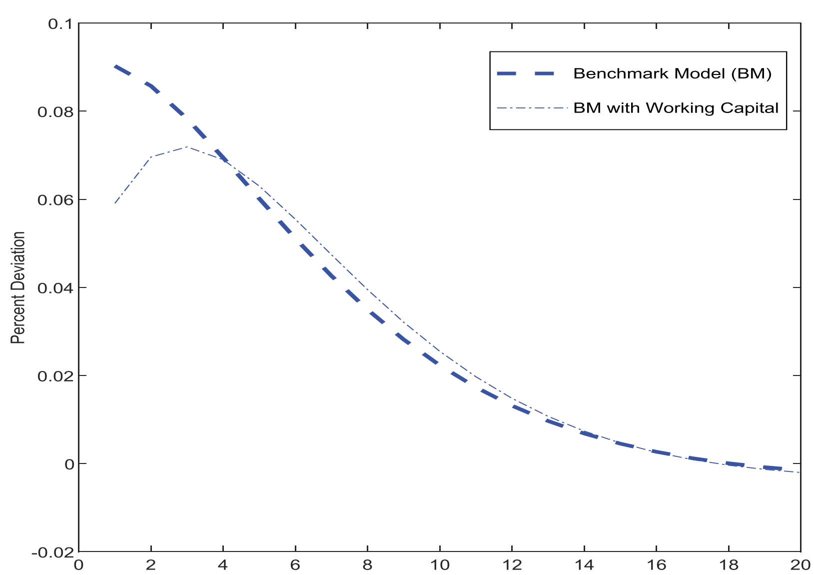

Figure 4. Hump-Shaped response of inflation.

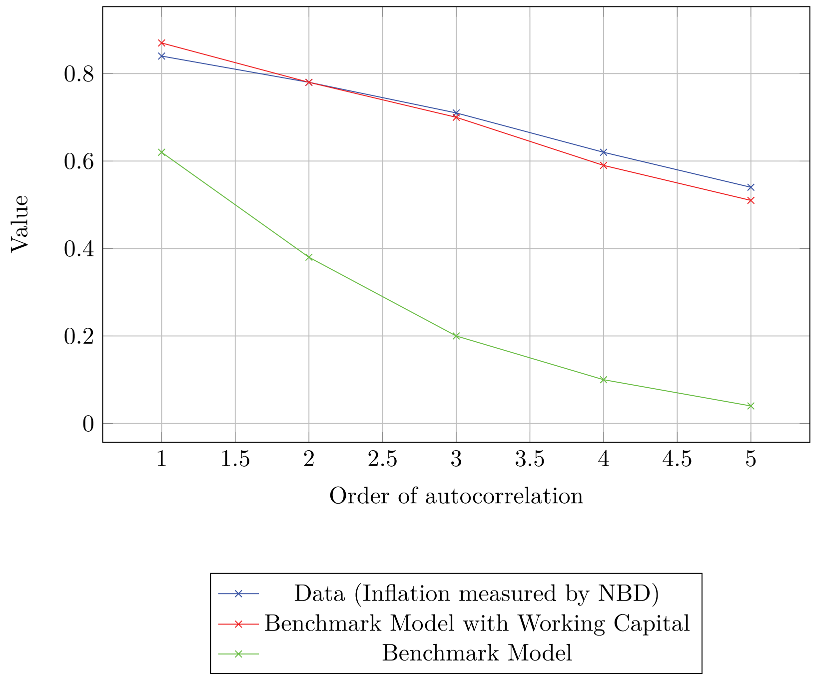

Figure 5. Inflation persistence in the benchmark model with working capital and data.

also Nelson 1998). Figure 5 compares the autocorrelations of price inflation in the data and those predicted by the benchmark model with working capital. With working capital added to sticky wages, sticky prices, and intermediate inputs, the autocorrelations of price inflation are closer to those observed in the data, ranging from 0.87 at the one-quarter lag to 0.51 at the four-quarter lag.

Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007) obtain persistent, hump-shaped responses of output, investment, and consumption in the aftermath of a monetary policy shock from DSGE models that omit roundabout production structure but include sticky prices and sticky wages, backward wage and price indexing, working capital and a choice of real frictions relatively similar to ours. Christiano, Eichenbaum, and Evans (2005) further impose that output, consumption, investment, aggregate price level, labour productivity, and real wage all respond to a policy shock with a one-period lag in the model to match the short-run restrictions imposed in an SVAR to identify a monetary policy shock. Here, we get similar results in a DSGE model that excludes backward-looking elements and adjustment lags to a monetary policy shock but includes sticky prices and wages, roundabout production, and endogenous monetary policy.

5.3. Varying calibration

Figure 6 shows that slight variations around our baseline calibration may exaggerate the hump-shaped pattern in the inflation response. For instance, increasing the investment adjustment cost parameter κ to 5 produces an even more hump-shaped response of inflation. The value of this parameter is either 3 or 5 based on estimates presented in Christiano, Eichenbaum, and Evans (2005) and Altig et al. (2011).

Note that the benchmark model's prediction of the inflation inertial behaviour roughly matches that found in Fuhrer and Moore's (1995) relative real wage contracting model, with the major difference that our findings are obtained using a full optimization-based DSGE framework.

5.4. Roundabout production and inflation dynamics

This section looks at the role of roundabout production in determining the short-run inflation dynamics in the aftermath of a monetary policy shock in the benchmark model with working capital. We answer this question by comparing the model impulse inflation responses to a 1-SD expansionary monetary policy shock with and without a roundabout production structure.

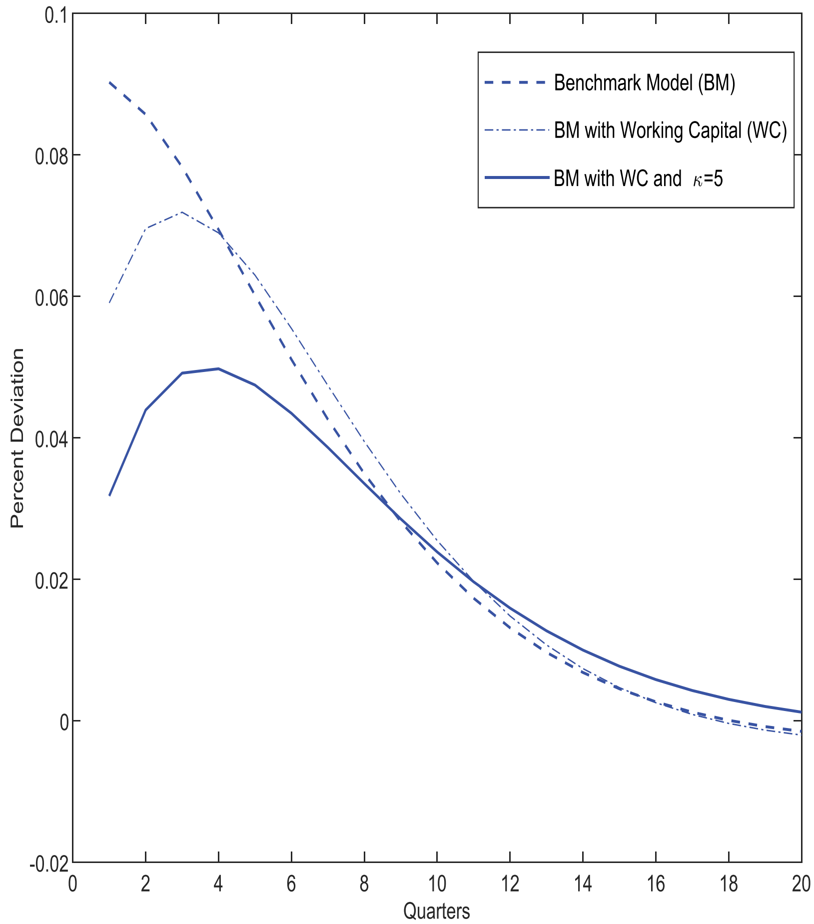

Figure 6. Impulse-responses of inflation and calibration.

Figure 7 shows the impulse responses of main macroeconomic variables to a negative shock to the nominal interest rate in the benchmark model with the working capital channel and without the roundabout production structure. Figures 7 and 8 show that the benchmark model with working capital cannot generate a hump-shaped inflation response to a monetary policy shock if we exclude the roundabout production structure even if we increase the investment adjustment cost parameter κ to 5. This finding suggests that the roundabout production structure is essential to the empirical success of our model. Consequently, the hump-shaped impulse inflation response is clearly determined by the interaction between the roundabout production structure and the working capital channel.

The link between inflation persistence and roundabout production structure can be explained as described in this section. Without this theoretical ingredient, the nominal marginal cost (Equation 18) records two flexible components in (R^k) and (RW). The real marginal cost (see Equation 19) adjusts strongly and rapidly in the aftermath of the policy shock, so inflation persistence is weak. When adding the roundabout production structure, the nominal marginal cost records three components. The additional component, which is the intermediate input price, is sluggish since all firms face sticky prices. The higher the share of intermediate input (ϕ), the less responsive real marginal cost is to variations in (R^k/P) and (RW/P). As a result, prices adjust less to the policy shock and are more sluggish. Consequently, inflation is more persistent.

The roundabout production structure is essential in obtaining a hump-shaped and persistent response of inflation. This production structure induces a strategic complementarity into the price setting, which increases price stickiness. Relative to the model with indexation, roundabout production dampens the response of inflation while making it more persistent at the onset of a monetary policy

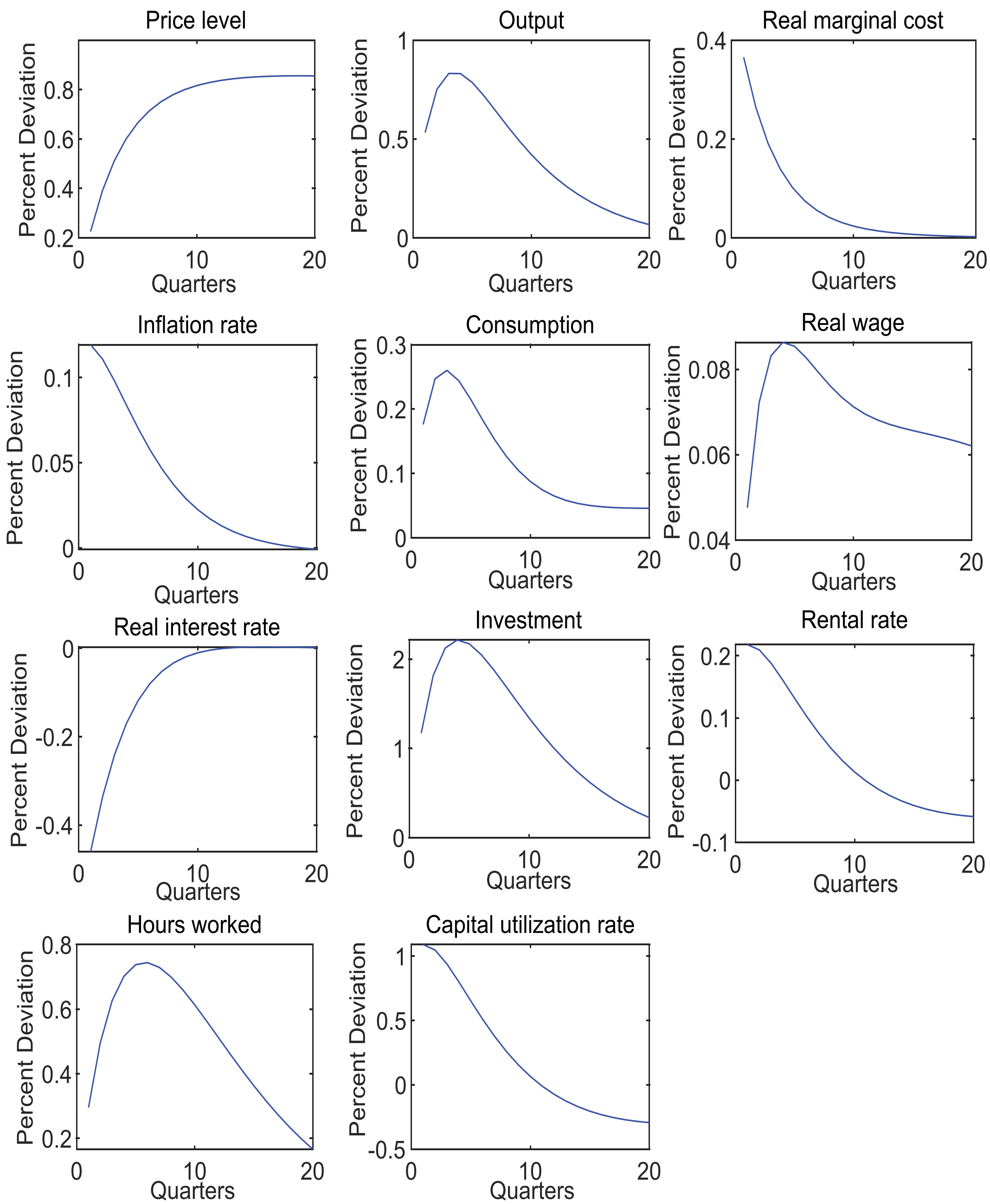

Figure 7. Impulse-responses in the benchmark model with working capital and without roundabout production structure.

shock. The cost channel helps obtain a hump-shaped response of inflation. The nominal interest rate directly affects marginal cost, which decreases initially following an expansionary monetary policy shock. Consequently, the cost channel induces hump-shaped inflation dynamics.

6. Conclusion

An important challenge macroeconomists must face is building DSGE models that can account for the persistent and hump-shaped responses of inflation to a monetary policy shock with the optimizing behaviours of firms and households and the rational expectations hypothesis. In contrast to some recent models that assume either short-run deviations from full optimization or slow-moving trend inflation, our article offers a macroeconomic framework entirely consistent with the optimizing behaviour of firms and households, while it also accounts for inflation inertia without relying on ad hoc backward components.

We propose a DSGE model incorporating endogenous monetary policy, sticky wages and prices,

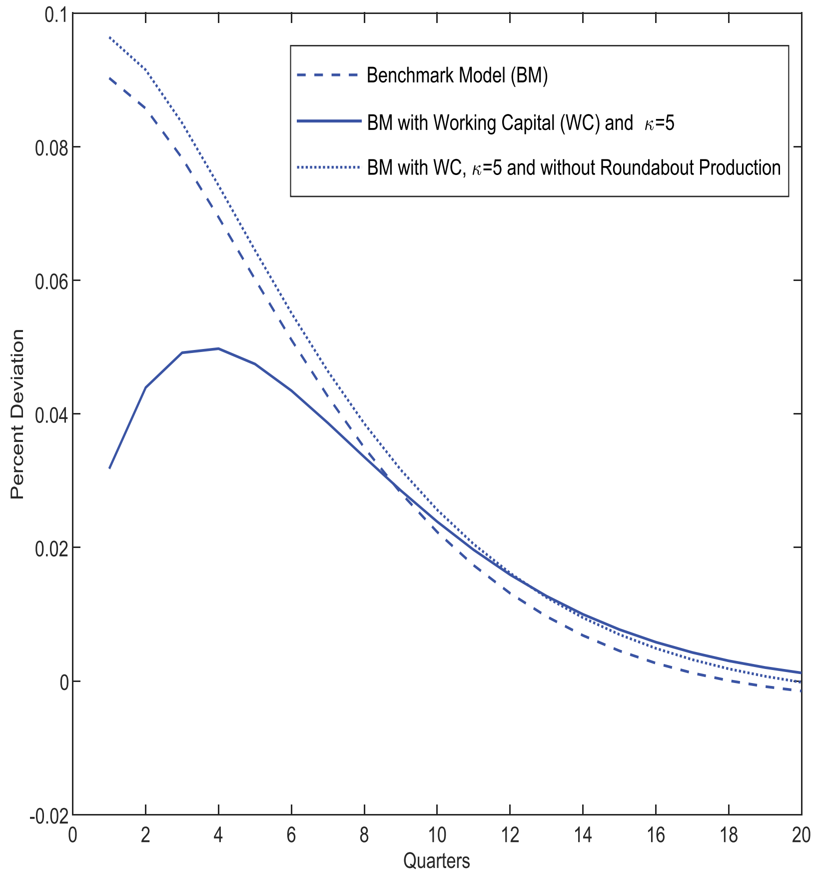

Figure 8. Impulse-responses of inflation in the benchmark model and its variants.

some real rigidities, working capital, and roundabout production structure. The results show that our model is consistent with a broad set of stylized facts relative to inflation that has been hard to explain without the ad hoc theoretical ingredients. Indeed, combining working capital with a roundabout structure helps the new Keynesian model generate highly serially correlated movements in inflation consistent with post-war United States data and a hump-shaped, persistent response of inflation to a monetary policy shock and then solve the inflation persistence puzzle as highlighted by Fuhrer and Moore's (1995).

While this study successfully captures the dynamic response of inflation to a monetary shock, it has the following limitation. Our results show that movement and persistence of inflation are sensitive to the value of the parameter controlling the size of investment adjustment costs. Consequently, even if the selected values of this parameter were within the consensus interval of the literature, a natural next step would be to estimate this parameter using the US post-war data and then re-investigate the empirical properties of our model. A second promising avenue of research will be to use our model to re-examine the questions studied by Arias et al. (2020) and Coibion and Gorodnichenko (2011) on the conditions for determining the equilibrium (determinacy) of monetary policy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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