Generalized Rotemberg Price-Setting

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Outline

Motivation

- In recent years, significant progress has been made in explaining microfacts of pricesetting behavior.
- This requires
  - models of heterogeneous firms
  - complex state-dependent pricing rules
  - typical ingredient: menu costs of price adjustment
- DSGE models
  - focus on aggregate outcomes
  - use simple, more tractable pricing models like those of Calvo or Rotemberg
  - provide good approximations to the aggregate responses to small shocks around a zero-inflation steady state
- However, it is well known that they fail to capture the observed nonlinear aspects of pricing behavior.

Three stylized facts of pricing behavior

1. **Nonlinear pass-through: Large shocks pass-through faster than small shocks**
   (Alvarez, Lippi, and Passadore 2017; Ascari and Haber 2022; Cavallo, Lippi, and Miyahara 2023)

2. **The higher the trend inflation, the steeper the New Keynesian Phillips curve, which effectively means that price flexibility is greater**
   (Benati 2007; Ball and Mazumder 2011; Costain and Nakov 2019; Gemma, Kurozumi, and Shintani 2023; Blanco, Boar, Jones, and Midrigan 2024)

3. **VAT changes have low announcement effects and comparatively large (but heterogeneous) implementation effects**
   (Karadi and Reiff 2019; Benzarti, Carloni, Harju, and Kosonen 2020; Benedek, De Mooij, Keen, and Wingender 2020)

The contribution of our paper I

- Generalization of the Rotemberg pricing model that is
  1. equally tractable and equivalent to the Rotemberg model up to second-order perturbations around a zero-inflation steady state, but
  2. able to capture the nonlinear behavior of inflation that is relevant in the presence of large shocks or positive trend inflation.
- Generalization by a symmetric sigmoid instead of a linear marginal cost function
- We analyze the properties of this model
  - → analytically, by deriving the pricing problem and the New Keynesian Phillips curve in discrete and continuous time, and
  - → numerically, by computing higher order perturbations and perfect foresight solutions.

The contribution of our paper II

We numerically analyze the properties of the model in three directions:

1. We demonstrate that the model can replicate the aggregate implications of standard forms of menu cost models.
2. We embed the generalized Rotemberg model in a basic DSGE framework, impose a parameter restriction such that the model is equivalent to the standard Calvo or Rotemberg model for small shocks around a zero-inflation steady state, and show that this model can explain the stylized facts mentioned above.
3. We illustrate that the model can reproduce the relationship between trend inflation and price flexibility at high rates of trend inflation to a similar extent as a complex state-dependent model of Costain and Nakov (2019).

Generalization of Rotemberg price-setting

- Monopolistically competitive firms face a demand function with constant elasticity of substitution $-\varepsilon$.
- Marginal costs MC_t are independent of firm output and the same for all firms.
- Firm i sets its price $P_{i,t}$ and receives $P_{i,t}/(1+\tau_t)$ for each unit sold, where τ_t is the value added tax (VAT).
- If the firm changes its price including VAT, it must pay price adjustment costs of $F\left(P_{i,t}/P_{i,t-1}-1\right)Y_tP_t$, where the nominal industry output Y_tP_t serves as adjustment cost base.
- The firm discounts future profits with the stochastic discount factor $\Lambda_{t,t+j}$.

The dynamic pricing problem and its solution

$$\max_{\{P_{i,t}\}_{t=0}^{\infty}} E_t \sum_{j=0}^{\infty} \Lambda_{t,t+j} \left\{ \left(\frac{P_{i,t+j}}{1+\tau_t} - MC_{t+j} \right) \left(\frac{P_{i,t+j}}{P_{t+j}} \right)^{-\varepsilon} Y_{t+j} - F\left(\frac{P_{i,t+j}}{P_{i,t+j-1}} - 1 \right) Y_{t+j} P_{t+j} \right\}$$

By taking the derivative with respect to $P_{i,t}$ and using that $P_{i,t} = P_t$ in equilibrium because of symmetry, we can write the aggregate first order condition in real terms as

$$\frac{(1-\varepsilon)}{1+\tau_t} + \varepsilon\, mc_t + \Lambda_{t,t+1} f\left(\pi_{t+1}\right)\left(1+\pi_{t+1}\right)^2 \frac{y_{t+1}}{y_t} = f\left(\pi_t\right)\left(1+\pi_t\right), \qquad (1)$$

where $mc_t = MC_t / P_t$ denotes real marginal costs inflation is defined as $\pi_t = P_t / P_{t-1} - 1$.

The classical Rotemberg model: $F\left(\pi_t\right) = \frac{\theta_R}{2}\pi_t^2; \quad f\left(\pi_t\right) = \theta_R \pi_t$.

The sigmoid marginal cost function

For the marginal cost of price adjustment we propose to use a *sigmoid* function, which is defined as a function on the real line with the following properties:

- it is bounded
- it is monotonically increasing
- it is differentiable
- there is exactly one inflection point x_0, and $\Sigma(x)$ is convex for $x \leq x_0$ and concave for $x \geq x_0$

We restrict attention to sigmoid functions Σ with inflection point $x_0 = 0$ that are symmetric in the sense that $\Sigma(-x) = -\Sigma(x)$, although one could easily allow for non-symmetric cost functions.

The sigmoid marginal cost function

We write the marginal cost function in general form as

$$f(\pi) = \theta_R \theta_S \Sigma\left(\frac{\pi}{\theta_S}\right), \qquad \theta_R \geq 0, \quad \theta_S > 0 \tag{2}$$

where $\Sigma : \mathfrak{R} -> [-1, 1]$ stands for any symmetric sigmoid function normalized such that $\Sigma(0) = 0$, $\Sigma'(0) = 1$ and $\lim_{\pi -> \infty} \Sigma(\pi) = 1$.

The product $\theta_R \theta_S$ is the upper limit of the marginal cost function.

The corresponding total cost function is given by $F(\pi) = \int_0^\pi f(x)dx$.

$$f'(\pi) = \theta_R \Sigma' \left(\frac{\pi}{\theta_S} \right) \geq 0 \tag{3}$$

- Since $\Sigma'(0) = 1$, the Rotemberg cost parameter θ_R determines the derivative of the marginal cost function at the origin.
- Symmetry implies $\Sigma''(0) = 0$ and therefore $f''(0) = 0$.
- Since classical Rotemberg has marginal cost function $\theta_R \pi$, this implies that GRP is equivalent to the classical linear Rotemberg model up to a quadratic approximation at the origin.
- The speed parameter θ_S determines the speed at which the sigmoid marginal cost function approaches the upper limit.

Examples of normalized sigmoid functions

$$\Sigma_1(x) = \operatorname{erf}\left(\frac{\sqrt{\bar{\pi}}}{2}x\right), \qquad \bar{\pi} = arccos(-1) \tag{4}$$

$$\Sigma_2(x) = \left(\frac{1-e^{-2x}}{1+e^{-2x}}\right) = \tanh(x) \tag{5}$$

$$\Sigma_3(x) = \frac{x}{\sqrt{1+x^2}} \tag{6}$$

$$\Sigma_4(x) = \frac{2}{\bar{\pi}}\arctan\left(\frac{\bar{\pi}}{2}x\right), \qquad \bar{\pi} = arccos(-1) \tag{7}$$

$$\Sigma_5(x) = \frac{x}{1+|x|} \tag{8}$$

Since π denotes inflation, as is common in the macroeconomic literature, we write the mathematical constant of the same name in $\Sigma_3(x)$ as $\bar{\pi}$.

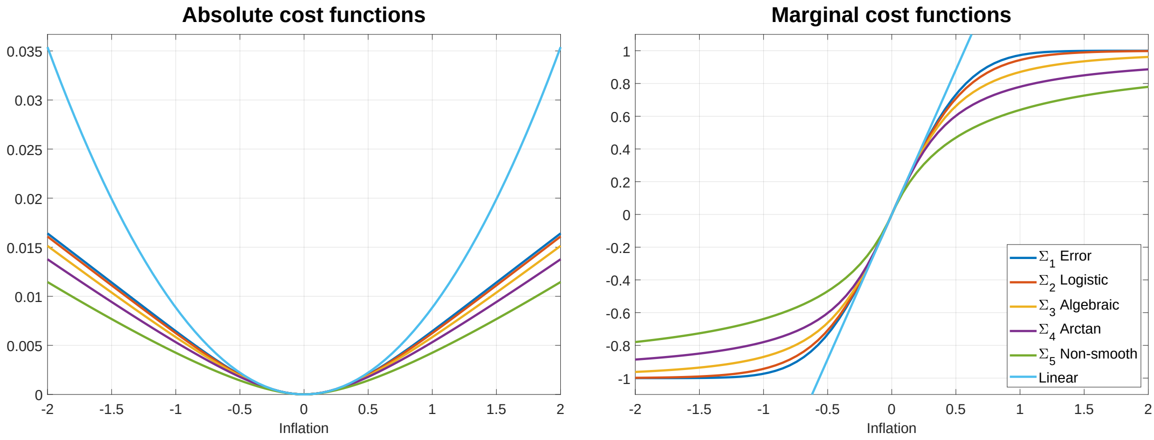


Figure: Examples of absolute and marginal cost functions

The sigmoid marginal cost function as generalization of the Rotemberg model

The marginal cost function (2) nests four pricing models as special or limit cases.

1. If θ_S goes to infinity, our model converges to the classical Rotemberg model in the sense that $f'(\pi) \to \theta_R$ for any π.
2. If $\theta_R = 0$, it holds that $F(\pi) = f(\pi) = f'(\pi) = 0$ and thus prices are flexible.
3. If $\theta_R \to \infty$ for any fixed θ_S, total costs of price adjustment go to ∞ for any $\pi > 0$, and thus optimal prices are constant in the limit.
4. (iv) If $\theta_S \to 0$ with $\theta_R\theta_S > 0$ fixed, the marginal cost of price adjustment converges to $\theta_R\theta_S$ for every $\pi > 0$ and to $-\theta_R\theta_S$ for every $\pi < 0$. The absolute cost function is linear with a kink at $\pi = 0$.

Calibration of the price adjustment cost parameters

- The Calvo parameter is usually justified on the basis of micro data, i.e. according to Costain and Nakov (2019) 10.2 percent of firms in the US adjust their prices every month which implies a Calvo parameter of $\theta_C = 0.898$.
- Typically, the Rotemberg parameter is justified on the basis of the Calvo parameter, taking advantage of the first-order equivalence of the two models.
- Compared to Calvo or Rotemberg pricing there is only the need to estimate θ_S. Possible calibration strategy:
  - We show in our paper that the slope of the Phillips curve is given by $\varepsilon / f'(\pi^*)$.
  - Blanco et al. (2024b) find that the slope of the quarterly Phillips curve increases by a factor of five if steady state inflation is 10 percent annually rather than 0 percent.
  - Generating this result in our model requires $f'(0.1) = 0.2 f'(0)$. This is satisfied by $\theta_S = 0.0785$ (at an annual rate) in the case of the arctan function.

A simple DSGE model

Households

$$w_t = \frac{\chi}{C_t^{-\sigma}},$$

$$R_t = \frac{C_t^{-\sigma}}{\beta C_{t+1}^{-\sigma}} (1 + \pi_{t+1}).$$

$$C_t = m_t$$

Firms

$$Y_t = \frac{z_t}{s_t} N_t.$$

$$mc_t = \frac{s_t}{z_t} w_t$$

Monetary policy

$$\frac{m_t}{m_{t-1}} = \frac{\mu e^{u_{m,t}}}{1 + \pi_t},$$

Market Clearing

$$Y_t = C_t$$

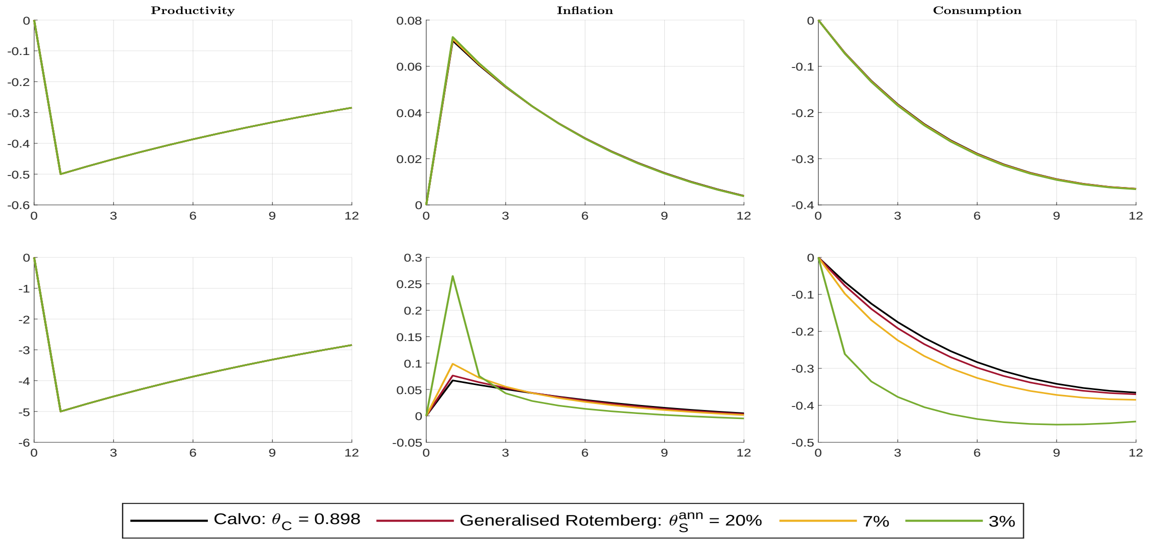
Shock processes

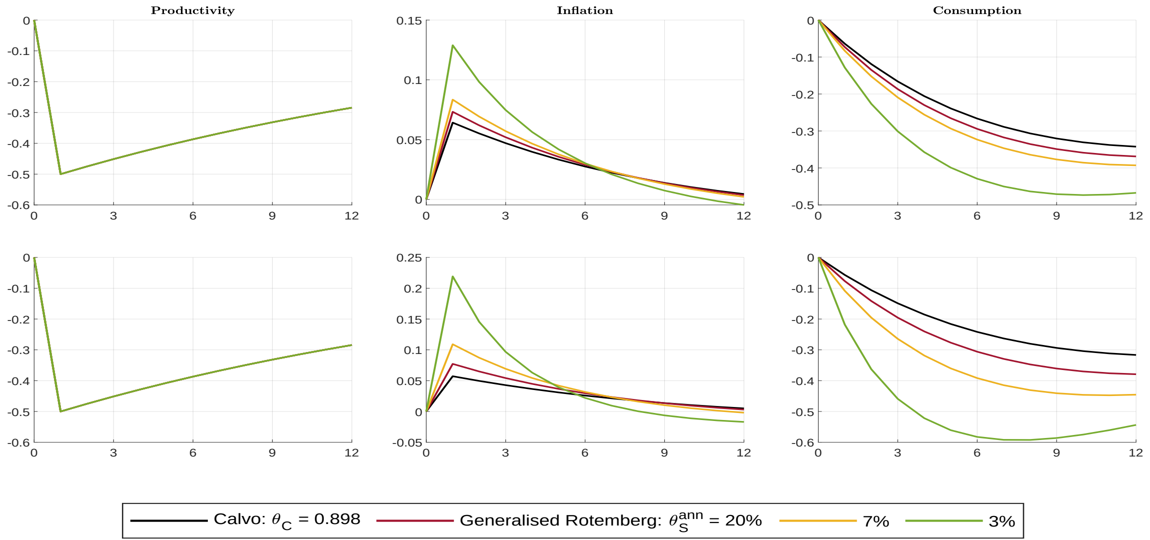
$$u_{m,t} = \phi_m u_{m,t-1} + \epsilon_t^{u_m}$$

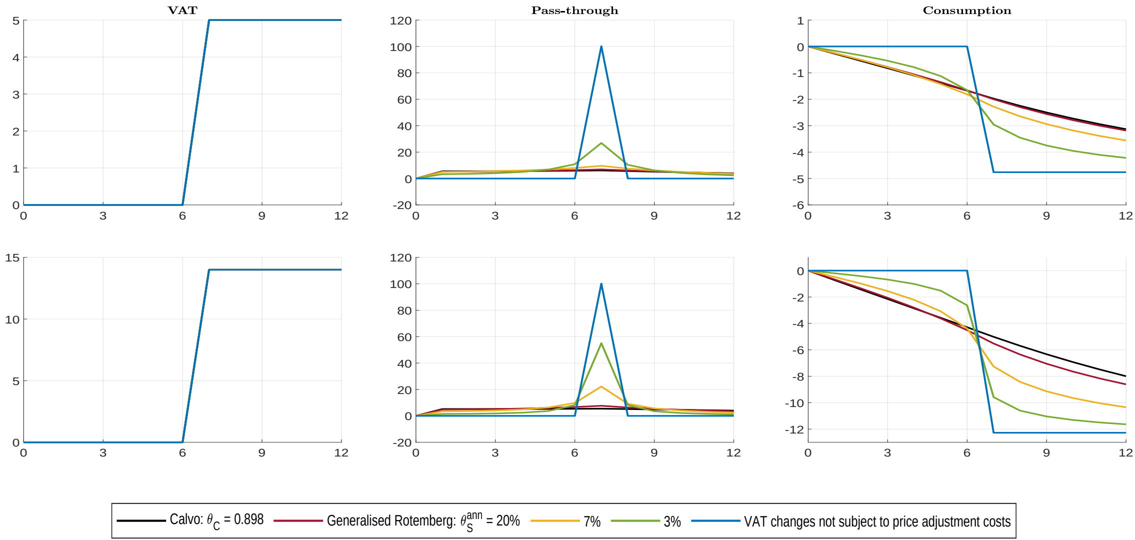
$$z_t = \phi_z z_{t-1} + \epsilon_t^z$$

Explaining the Stylized Facts

- The following figures compare the impulse responses of the generalized Rotemberg model using different calibrations with those of the Calvo model.
- The productivity shocks have a persistence of 0.95.
- The Rotemberg parameter θ_R is always set to a value such that the model is equivalent up to a first order approximation around the zero inflation steady state to a Calvo model with $\theta_C = 0.898$.
- The figures then show impulse responses for different speed parameters.
- The impulse responses of inflation and consumption (second and third columns of the figures) are each divided by the shock size except in the case of the VAT shock.


Productivity
Inflation
Consumption
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0.08
0.06
0.04
0.02
0 3 6 9 12
-1
-2
-3
-4
-5
-6
0.3
0.25
0.2
0.15
0.1
0.05
-0.05
Calvo: θ_C = 0.898
Generalised Rotemberg: θ_S^{ann} = 20%
7%
3%


Productivity
Inflation
Consumption
Calvo: θ_C = 0.898
Generalised Rotemberg: θ_S^{ann} = 20%
7%
3%


VAT
Pass-through
Consumption
Calvo: θC = 0.898
Generalised Rotemberg: θS ann = 20%
7%
3%
VAT changes not subject to price adjustment costs

Take-Home Message

1. Generalized Rotemberg Pricing can account for important aspects of the observed nonlinear behavior of price adjustment at the macroeconomic level, such as
    - higher pass-through in response to larger shocks,
    - a positive impact of trend inflation on the slope of the NKPC and on price flexibility, and
    - the relationship between announcement and implementation effects of tax changes.
2. In the paper we demonstrate that with an appropriate calibration, it can generate
    - similar effects on macroeconomic variables as standard menu-cost models
    - effects of high trend inflation on price flexibility very similar to a recent, much more complex model of logit price dynamics
3. Compared to a standard Calvo or Rotemberg model, our model requires the estimation of only one additional parameter, which we call the speed parameter θ_S.
4. Generalized Rotemberg pricing is easy to apply, does not introduce additional state variables, and is equivalent to the classical Rotemberg model for sufficiently small shocks.

Thank you for your attention!

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Limitations and future research

- If a model of heterogeneous firms with idiosyncratic shocks is the ”true” model, our representative firm model is not structural in the sense of Lucas (1976).
- We see a major application of our price-setting scheme in multi-industry DSGE models, because shocks at the industry level are larger than aggregate shocks, so that nonlinearities become very important.
- The size of these models makes it very difficult to handle heterogeneous firms, so that the tractability of the generalized Rotemberg model is a big advantage. Estimating such a model is part of our research agenda.

Related literature

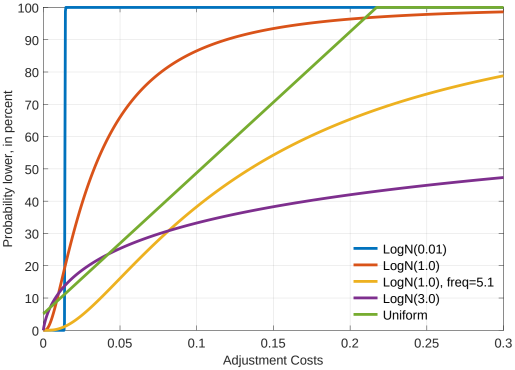
- Large literature on menu costs and the (non)neutrality of money (Barro 1972; Mankiw 1985; Golosov and Lucas 2007; Caballero and Engel 2007; Alvarez, Le Bihan, and Lippi 2016; Auclert, Rigato, Rognlie, and Straub 2024)

- Large literature that attempts to explain increasingly detailed stylized facts by constructing increasingly complex models of price setting
  → Early review: Nakamura and Steinsson (2013)
  → Important recent contributions: Costain and Nakov (2019), Karadi and Reiff (2019), Ilut et al. (2020) and Dotsey and Wolman (2020)

- Convex costs of price adjustment (Rotemberg 1982; Rotemberg 2011)
  → Zbaracki et al. (2004) conclude that many components of managerial and customer costs are convex, that is larger price changes incur higher costs.

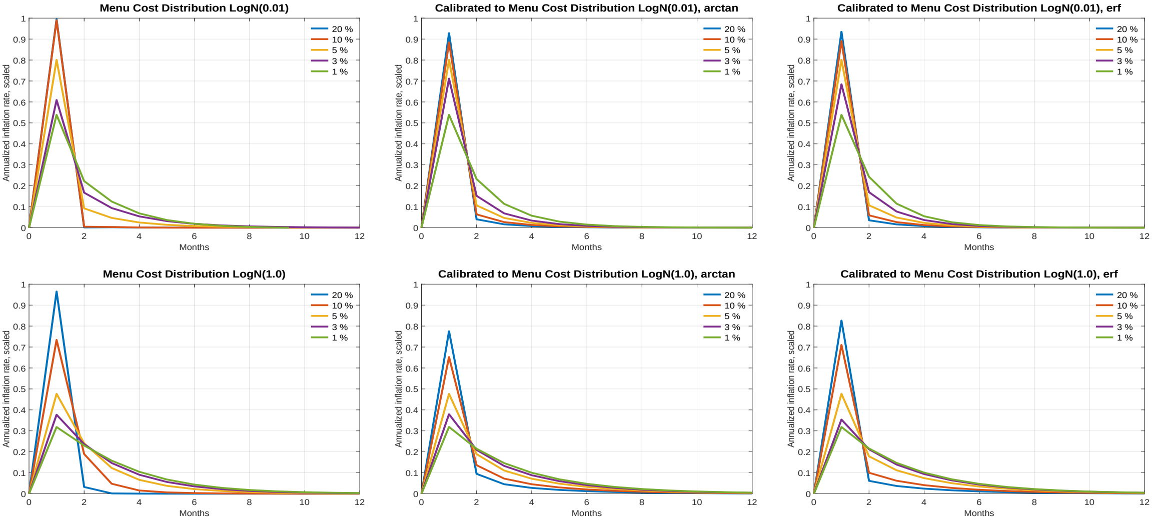
Generalized Rotemberg pricing versus menu costs

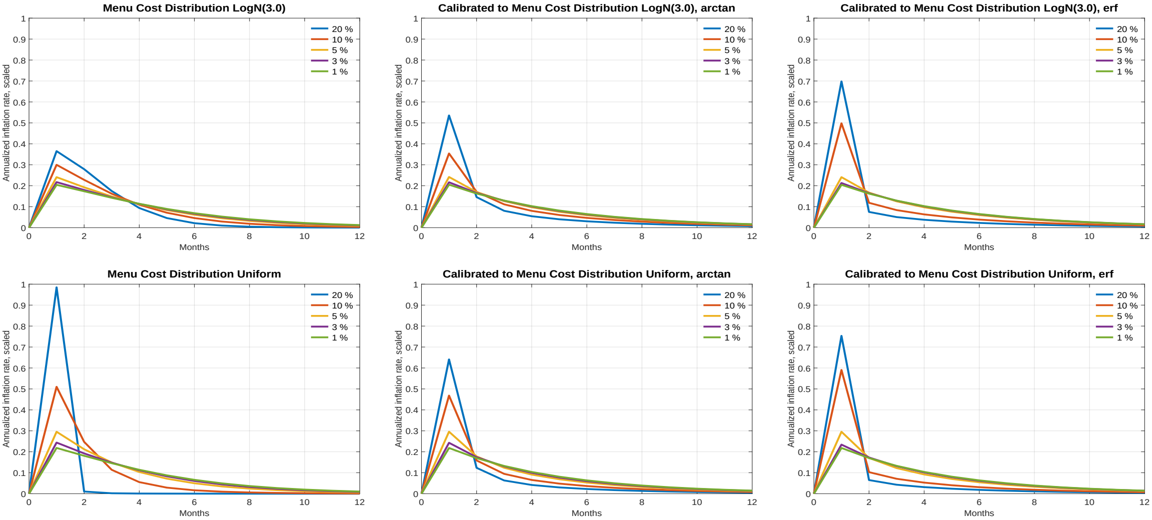
- Partial equilibrium: Industry under monopolistic competition subject to a sudden permanent increase in marginal costs
- The industry is populated by a continuum of ex ante identical firms.
- The only endogenous firm-specific state is the nominal price $p_{i,t}$.
- Changing the price is subject to menu costs which are potentially stochastic and independent over time and across firms.



Approach

- For each version of the menu cost model, we calibrate the parameters θ_B and θ_S so as to best match the impulse responses to the 1 percent and 5 percent shocks, measured as the sum of squared deviations of the scaled impulse responses on impact after the shock.
- For the calibration and for the following pictures, impulse responses are always scaled down by the size of the shock (which can be negative), so that they are comparable to the response of a 1 percent shock.


Menu Cost Distribution LogN(0.01)
Calibrated to Menu Cost Distribution LogN(0.01), arctan
Calibrated to Menu Cost Distribution LogN(0.01), erf
Menu Cost Distribution LogN(1.0)
Calibrated to Menu Cost Distribution LogN(1.0), arctan
Calibrated to Menu Cost Distribution LogN(1.0), erf
Annualized inflation rate, scaled
Months
20 %
10 %
5 %
3 %
1 %
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12


Menu Cost Distribution LogN(3.0)
Calibrated to Menu Cost Distribution LogN(3.0), arctan
Calibrated to Menu Cost Distribution LogN(3.0), erf
Menu Cost Distribution Uniform
Calibrated to Menu Cost Distribution Uniform, arctan
Calibrated to Menu Cost Distribution Uniform, erf
Annualized inflation rate, scaled
Months
20 %
10 %
5 %
3 %
1 %

Calibration

Our results do not depend on the exact calibration. For the sake of completeness:

- The discount factor β is set to $1.04^{-1/12}$, the steady state growth rate of the money supply $\mu = 1.00$, unless stated otherwise, and the elasticity of substitution ε is set to 7.
- We set the intertemporal elasticity of consumption $\sigma = 1$ and the Frisch elasticity of labor supply φ to 0.
- We set χ in a way that steady state labor supply is roughly 1/3.
- The steady state VAT τ is set either to 20 percent when the VAT is a changing variable, otherwise it is set to zero.

Adaption of the model to Costain and Nakov (2019)

Households maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\sigma}}{1-\sigma} - \chi \frac{N_t^{1+\varphi}}{1+\varphi} + \nu \ln \left(\frac{M_t}{P_t} \right) \right],$$

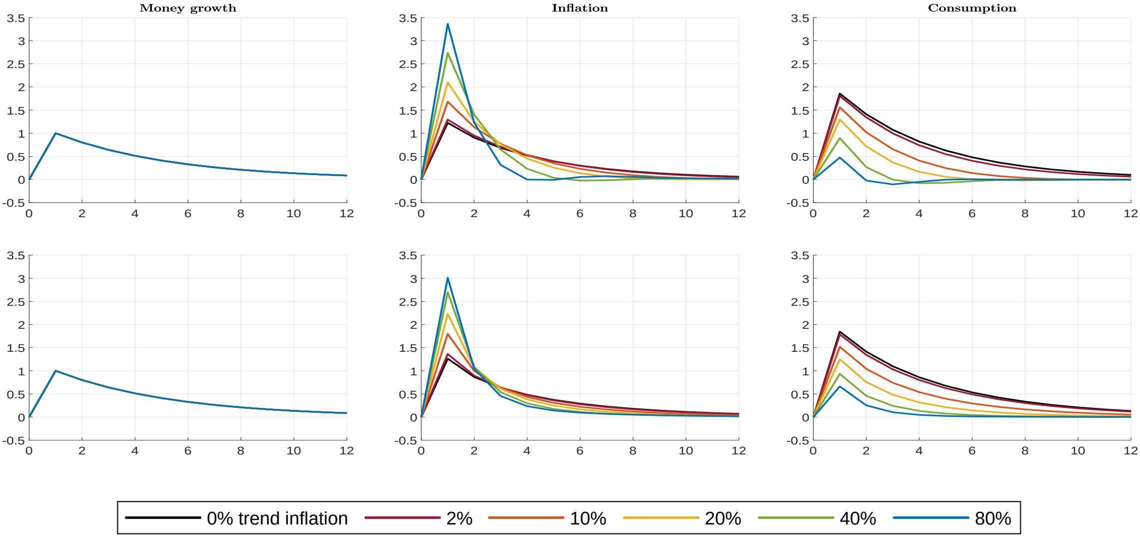
subject to

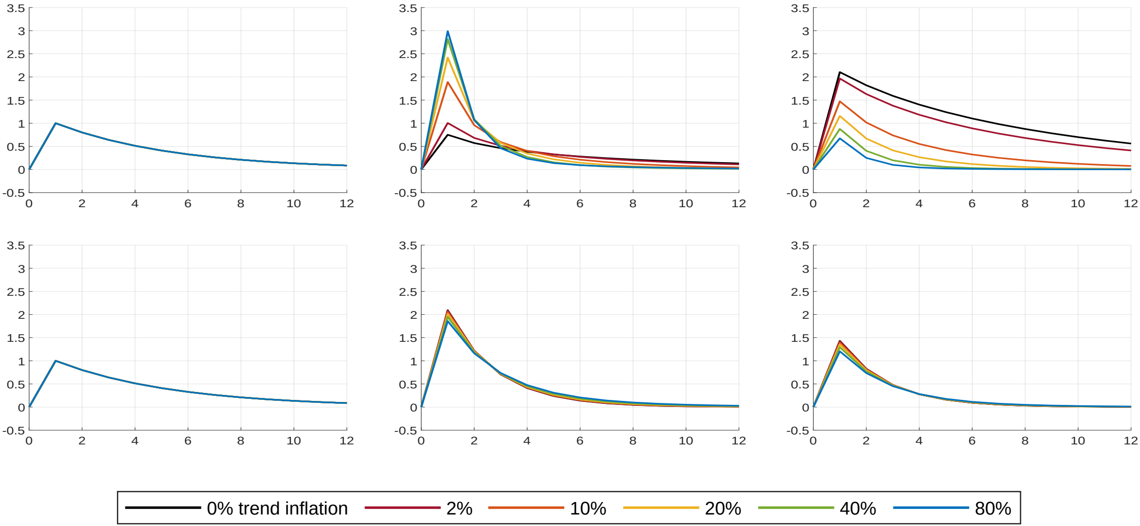
$$C_t + m_t + \frac{b_t}{R_t} = w_t N_t + \frac{m_{t-1} + b_{t-1}}{1+\pi_t} + T_t.$$

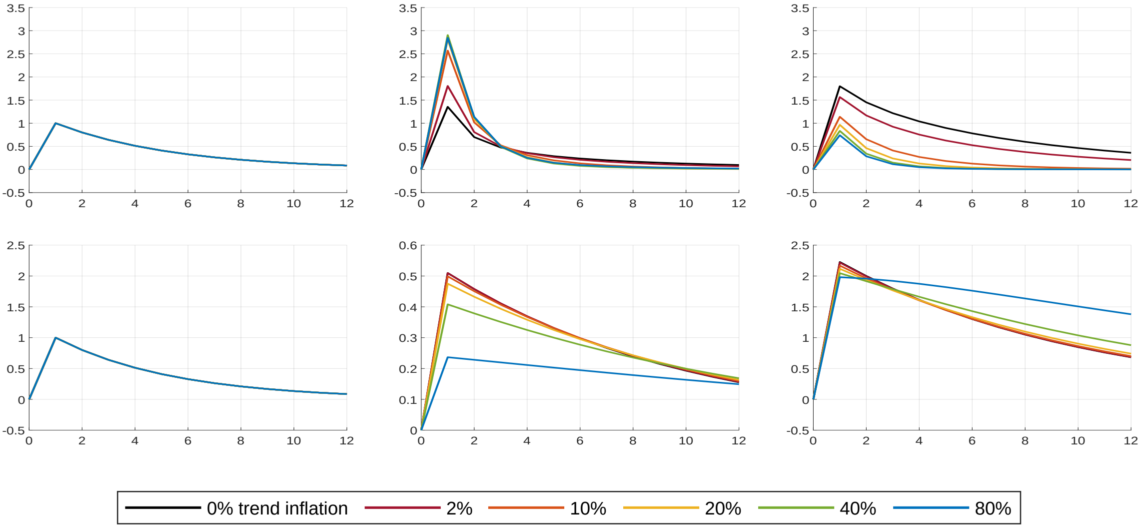
Replace the cash-in-advance constraint with the first-order condition for money demand:

$$\frac{\nu}{m_t} = 1 - \frac{1}{R_t} \tag{9}$$

Moreover, we calibrate $\nu = 1$, $\sigma = 2$ and $\chi = 6$, exactly as in Costain and Nakov (2019).


Money growth
Inflation
Consumption
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
2
4
6
8
10
12
0% trend inflation
2%
10%
20%
40%
80%


0% trend inflation
2%
10%
20%
40%
80%


0% trend inflation
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