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Matthias Paustian, Bowling Green State University
Jürgen von Hagen, University of Bonn, Indiana University and CEPR

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Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: www.cepr.org

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ABSTRACT

The Role of Contracting Schemes for Assessing the Welfare Costs of Nominal Rigidities*

Due to the lack of pertinent evidence, there is currently no agreement on how to introduce nominal rigidities into monetary macroeconomic models. We examine the role of alternative assumptions about the wage and price setting mechanisms for the assessment of the welfare costs of nominal rigidities and the performance of alternative monetary policy rules in an otherwise standard New Keynesian general equilibrium model. We find that the choice of a particular price and wage setting scheme matters quantitatively for the welfare costs of nominal rigidities. However, qualitative statements such as the welfare ranking of alternative monetary policy rules are robust to changes in contracting schemes. The difference between sticky nominal contracts and sticky information matters more than the difference in the age distribution of prices wages and information implied by alternative price and wage setting schemes.

JEL Classification: E32 and E52
Keywords: Calvo pricing, monetary policy rules, nominal rigidities, sticky information and Taylor contracts

Matthias Paustian
Department of Economics
302 Business Administration Bldg.
Bowling Green State University
Bowling Green
OH 43403
US
Email: paustim@bgsu.edu

Jürgen von Hagen
University of Bonn
Department of Economics
Lennestrasse 37,
53113 Bonn
GERMANY
Email: vonhagen@uni-bonn.de

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1 Introduction

A large part of contemporary monetary macroeconomics builds on the assumption of nominal rigidities to explain the propagation of macroeconomic shocks and macroeconomic dynamics at cyclical frequencies. Such rigidities are an essential ingredient of the New Keynesian macroeconomic (NKM) models commonly used to study short-run fluctuations and optimal monetary and fiscal policies. Their importance is underscored by recent estimates indicating that the welfare costs of nominal rigidities may range between one and three percent of annual consumption, see Canzoneri, Cumby, and Diba (2007). That is, a typical consumer would give up between one and three percent of his consumption to move from a world with nominal rigidities to a world without. A policy implication of these estimates is that, if, in a world with nominal rigidities, optimal monetary policy can approximately replicate the allocation that would prevail in a world without nominal rigidities, it can achieve substantial welfare gains.

Despite the widespread agreement, however, that nominal rigidities matter, there is little agreement among economists today on the most appropriate price and wage-setting mechanism that should be used to model them. The most widely used mechanism in the literature is the pricing rule proposed by Calvo (1983), which assumes that in each period some firms (workers) are randomly chosen and allowed to adjust their prices (wages) to current and expected future macroeconomic circumstances, while all others hold their prices fixed. This mechanism owes its popularity to its analytical convenience, but its drawbacks are by now well understood. With a fixed probability of price adjustment each period, some firms do not get to adjust their prices for arbitrarily long periods of time. This generates relative price distortions which make the welfare costs of nominal rigidities implausibly large; see Kiley (2002) and Ascari (2004). A variety of alternatives to the Calvo mechanism have been introduced in the recent macroeconomic literature and a number of empirical micro and macro studies on these mechanisms exist. Nevertheless, the evidence for or against a particular mechanism is far from being conclusive.[1] As a result, it is still largely up to the individual researcher to choose a mechanism generating price and wage rigidities as a basis of his analysis.

This situation is unsatisfactory. Not knowing how much the differences in the price and wage setting mechanisms matter, it is difficult to compare different studies of the welfare costs of nominal rigidities using different mechanisms. Furthermore, it is particularly awkward for monetary policy makers. If alternative monetary policy rules perform very differently when evaluated on the basis of models with different price and wage setting schemes, central bankers would need to know a lot about which of these schemes are empirically relevant and how robust the policy rules are under alternative price and wage

[1] See the recent work by Laforte (2007) for the empirical macro evidence on alternative pricing schemes. The work of the European Central Bank's Inflation Persistence Network summarized in Angeloni, Aucremanne, Ehrmann, Gali, Levin, and Smets (2007) presents further empirical evidence on price stickiness. Altissimo, Ehrmann, and Smets (2006) note that firms in the euro area change prices infrequently, but revise prices more frequently.

setting mechanisms. In this regard, Canzoneri, Cumby, and Diba (2007) note that there is a general consensus in the NKM literature that, in the presence of price rigidities alone, the optimal monetary policy rule aims at price stability alone regardless of the specific mechanism generating price inertia. They indicate, however, that things might get more complicated and that there is less agreement on optimal policy rules, when both price and wage rigidities prevail.

The goal of this paper is to explore how the choice of specific price and wage setting mechanisms affects the welfare costs of nominal rigidities in a dynamic general equilibrium model and the performance of alternative monetary policy rules. For this purpose, we present a standard NKM model with differentiated intermediate goods and labor based on Erceg, Henderson, and Levin (2000). We calibrate and simulate this model assuming different pricing and wage setting mechanisms and obtain estimates of the welfare costs of nominal rigidities for a wide range of structural parameter values of the model.[2] Furthermore, we simulate the model under alternative monetary policy rules to explore how sensitive the performance these rules is to changes in the price and wage setting mechanisms.

Together with a conventional Calvo scheme, we consider a truncated Calvo mechanism, which specifies a maximum length of time between any two price adjustments for all firms. Furthermore, we examine the mechanism proposed by Wolman (1999) which is characterized by price adjustment probabilities that increase as the lag since the last adjustment becomes longer, and Taylor (1980) contracts, which specify a fixed period of duration for each price set by a firm and each wage set by workers.[3]. In addition, we follow Mankiw and Reis (2002), who propose a price and wage setting scheme based on the assumption that firms (workers) are allowed to adjust their prices (wages) every period, but they do not receive new information relevant for doing so every period. Under this sticky-information mechanism, price and wage adjustment is sluggish because of the informational rigidities.

Our main findings can be summarized as follows. First, the welfare costs of nominal rigidities differ substantially across alternative price and wage-setting schemes. For a given average age of the price and wage contracts in an economy, schemes that place more mass on older contracts imply larger welfare costs of nominal rigidities. The intuition is that there are larger relative price and wage distortions when some agents have not updated their prices and wage contracts for a longer time. For example, nominal price and wage rigidities based on Calvo contracts generate welfare costs that are up to 2.5 times bigger than those implied by Taylor contracts with the same average age. Truncating the duration of Calvo contracts after ten quarters reduces the welfare costs under this scheme, but only slightly so. The Wolman pricing scheme leads to substantially lower welfare costs than Calvo pricing, but larger costs than Taylor contracts.

Second, while alternative monetary policy rules imply large differences in the welfare

[2]To make the different price and wage setting schemes comparable, we require that the average age of contracts is the same across alternative schemes.

[3]See Fischer (1977) for a similar model using overlapping wage contracts.

costs of nominal rigidities given a particular price and wage setting mechanism, the ranking of the welfare costs associated with alternative price and wage setting mechanisms is largely invariant to the monetary policy rule used. Thus, qualitative comparisons of the welfare costs of such mechanisms do not hinge on knowing which rule the central bank applies.

Third, similar results hold for different assumptions about updating the information sets in sticky information models. For a given average age of information sets, updating schemes that put less mass on older information involve smaller welfare costs. Quantitatively, the effect is more pronounced than with sticky prices and wages. For example, Calvo style updating rules can involve welfare costs that are up to five times larger than those of Taylor-type updating rules with the same average age.

Fourth, these results are robust to several sensible model variations. They are the same when we assume that the central bank measures the output gap as deviations from flexible price and wage output rather than from steady state output. They are confirmed when we assume that capital is fixed at the firm level rather than mobile due to the existence of an economy-wide rental market for capital. They are robust to variations of the critical parameters of the model across a wide range of values. They hold regardless of whether the economy is predominantly hit by technology shocks, monetary shocks, or preference shocks.

Finally, while alternative pricing and wage setting schemes are associated with different welfare costs, the welfare *ranking* of alternative monetary policy rules is very robust to changes in the mechanism generating nominal rigidities in the economy. Thus, an important policy implication of our analysis is that central banks do not have to know much about what generates the nominal rigidities in their economies. A monetary policy rule producing relatively good results under one mechanism will do so under others. In our environment with price and wage rigidities, monetary policy rules emphasizing wage stability fare best in terms of welfare. However, the welfare ranking of other monetary policy rules in a Mankiw and Reis (2002) setting differs considerably from the ranking in a conventional sticky-price and wage setting.

Our findings extends the related work by Kiley (2002) and Ascari (2004), who show that Calvo contracts imply higher welfare costs of steady state inflation than Taylor (1980) contracts. However, these authors do not explore the role of contracting schemes over the business cycle as we do. Dixon and Kara (2005) compare Calvo with Taylor pricing mechanisms, but they also focus only on a steady state analysis. Finally, Nistico (2007) compares Calvo with Rotemberg pricing when the steady state is efficient. He shows that both models imply the same welfare costs of inflation. Dixon and Kara (2006b) embed a variety of wage setting schemes in a NKM model in an approach similar to our's. However, these authors ask a question different from our's, namely, which wage setting scheme yields the best approximation to the observed inflation dynamics in the Euro area. They find that Calvo contracts perform worst, but other mechanisms generating a distribution of lengths provide relatively good empirical approximations.

This paper compares alternative economies with the same price and wage setting mechanisms but different monetary policy rules as well as economies with the same structural parameterizations but different price and wage setting mechanisms. Implicitly, therefore, it assumes that structural parameters and price and wage setting mechanisms can be varied independently of each other. However, price and wage setting mechanisms are an important part of the behavior of firms and workers, and it is natural to assume that, ultimately, they are the result of optimizing behavior of the economic agents in the model. Thus, one might argue that our exercise is subject to the Lucas (1976) critique. It is likely that the agents in an economy characterized by a given set of structural parameters systematically select the wage and price setting mechanisms that are in their best interest given their environment. The implication would be that some combinations of price and wage setting mechanisms on the one hand and structural parameters on the other are irrelevant, while others are more likely to emerge and should be the ones we focus on. While we recognize this possibility, we think that it does not change the comparative results of our paper, as it would merely shrink the set of parameter values in which the same results hold. In any case, there is currently simply not enough evidence on the principles that guide the choice of price and wage setting mechanisms. Thus, we interpret our exercise as a methodological contribution tracing out the welfare implications of different ways to model nominal rigidities and of devising monetary policy strategies given this uncertainty.

The paper proceeds as follows. Section 2 introduces the setup of the model. Section 3 describes the alternative wage and price setting schemes. Section 4 presents the model's baseline calibration. Section 5 computes the welfare costs of nominal rigidities across our considered schemes. Section 6 concludes.

2 Model setup

Our model is based on Erceg, Henderson, and Levin (2000). Capital is in fixed supply in the aggregate, and there is an economy-wide rental market that allows capital to move freely between firms. In a subsequent robustness check, we will assume that capital is fixed at the firm level. Subsidies exist that completely offset the effects of monopolistic competition in the steady state. Households can fully insure against the income risk arising from nominal wage rigidities.

2.1 Households

We consider the cash-less limit of a money-in-the-utility-function framework. There is a continuum of households with unit mass indexed by h. Households are infinitely lived. A household h consumes final goods $C_t(h)$ and supplies labor of type h, $N_t(h)$. Its preferences are described by the instantaneous utility function:

$$\mathbb{W}_t(h) \equiv \xi_t \frac{C_t^{1-\sigma}(h)}{1-\sigma} - \frac{N_t^{1+\chi}(h)}{1+\chi}. \tag{1}$$

Here, ξ_t is a preference shock. The household receives a nominal wage $W_t(h)$. It purchases state-contingent securities $B_t(h)$, each of which pays one unit money in a particular state of nature in the subsequent period. These bonds provide the households with perfect consumption insurance against labor income risk stemming from nominal wage rigidities. The price of these bonds is denoted by $\delta_{t+1,t}$. Furthermore, each household receives an equal share of profits and rental incomes $\Gamma_t(h)$. The decision problem of household h is:

$$\max_{\{B_{t+i},C_{t+i}\}_{i=0}^{\infty}} E_t \sum_{i=0}^{\infty} \beta^i \mathbb{W}_i(h) \quad \text{s.t.}$$
$$C_{t+i}(h) = \tau_w \frac{W_{t+i}(h)}{P_{t+i}} N_{t+i}(h) + \Gamma_{t+i}(h) - \frac{\delta_{t+1+i,t+i} B_{t+i}(h) - B_{t+i-1}(h)}{P_{t+i}}.$$

τ_w is a wage subsidy used to offset the steady state effects of monopolistic competition in the labor market and P_t is the aggregate price index. The first-order conditions for consumption and state contingent bond holdings give rise to the standard Euler equation, where we have dropped the index h due to perfect insurance

$$\xi_t C_t^{-\sigma} = E_t \beta \left\{ \frac{P_t}{P_{t+1}} \xi_{t+1} C_{t+1}^{-\sigma} \right\} R_t^n. \tag{2}$$

Here, R_t^n is the nominal interest rate that would be paid on a non-contingent bond. The household supplies whatever amount of labor demanded at the nominal wage posted. We discuss the wage setting problem in a later section, when we define the contracting schemes.

2.2 Production

There is a final goods sector and an intermediate goods sector. Firms in the perfectly competitive final goods sector produce a homogeneous consumption good, Y_t, using intermediate goods, $Y_t(z)$, as inputs. The production function that transforms intermediate goods into final output is given by the aggregator $Y_t^{(\epsilon-1)/\epsilon} = \int_0^1 Y_t(z)^{(\epsilon-1)/\epsilon} dz$. This gives rise to the following demand function for variety z of the intermediate good: $Y_t(z) = (P_t(z)/P_t)^{-\epsilon} Y_t$. Here, P_t is the aggregate price level defined by $P_t^{1-\epsilon} = \int_0^1 P_t(z)^{(1-\epsilon)} dz$. The intermediate goods sector consists of a continuum monopolistically competitive firms indexed by $z \in [0, 1]$ and owned by the consumers. Each firm produces one variety of the intermediate good. A labor bundler aggregates individual labor $N_t(h)$ into composite labor L_t according to $L_t^{(\kappa-1)/\kappa} = \int_0^1 N_t(h)^{(\kappa-1)/\kappa} dh$. This gives rise to the following demand function for labor of type h: $N_t(h) = (W_t(h)/W_t)^{-\kappa} L_t$, where $W_t^{1-\kappa} = \int_0^1 W_t(h)^{(1-\kappa)} dh$ defines the aggregate wage index.

Intermediate goods firms use their composite labor inputs $L_t(z)$ and capital $K_t(z)$ to produce intermediate goods according to the following constant returns technology:

$$Y_t(z) = A_t L_t(z)^{1-\alpha} K_t(z)^{\alpha}. \tag{3}$$

Here, A_t denotes total factor productivity, which follows an exogenous AR(1) process. Intermediate goods firms rent capital in a competitive market on a period by period basis after observing the aggregate shocks. Firm z chooses $L_t(z)$ and $K_t(z)$ to minimize total cost subject to meeting demand. From the cost minimization problem, we have the following two optimality conditions

$$w_t^r = (1-\alpha)X_t(z)A_tK_t(z)^{\alpha}L_t(z)^{-\alpha}, \tag{4}$$
$$Z_t = \alpha X_t(z)A_tK_t(z)^{\alpha-1}L_t(z)^{1-\alpha}. \tag{5}$$

Here, w_t^r is the real wage, Z_t the real rental rate for capital and $X_t(z)$ denotes real marginal cost. The first-order conditions imply that all firms choose the same capital- to-labor ratio, hence marginal cost X_t is equalized across firms. Therefore, (4) and (5) also hold when evaluated at the aggregate capital-labor ratio.

2.3 Monetary policy

Monetary policy is assumed to a follow log-linear interest rate rule:

$$\hat{R}_t^n = (1-\alpha_2)\left[\alpha_0 gap_t + \alpha_1\hat{\pi}_t + \alpha_3\hat{\pi}_t^w\right] + \alpha_2\hat{R}_{t-1}^n + m_t. \tag{6}$$

Here, gap_t refers to the output gap, π_t is the rate of price inflation, π_t^w denotes the rate of wage inflation, m_t is an i.i.d. monetary policy shock, and hatted variables denote log deviations from the steady state. Monetary policy reacts to price and wage inflation and the output gap. We assume that the long run inflation rate is zero.

In the baseline scenario, we take the gap to be the deviation of output from steady state, i.e. $\hat{Y}_t$. One may object that the *welfare relevant* output gap is instead the deviation of output from its level under flexible prices and wages, $\hat{Y}_t^*$. However, such a gap measure would be considerably more difficult to compute for central banks and, therefore, difficult to implement in practice. We report welfare costs for this measure of the gap as well in a later robustness check.

3 Price and wage setting

3.1 Price and wage setting under sticky contracts

We consider a variety of contracting schemes, which differ in the probability that a price or wage contract that was last updated in period $t-j$ can be adjusted in period t, where $j \geq 0$. Apart from standard Calvo (1983) contracts, we consider a truncated version of that scheme assuring that no price or wage is older than ten periods, the scheme proposed by Wolman (1999) with adjustment probabilities that increase over time, and overlapping, fixed-term contracts as proposed by Taylor (1980). We use the truncated Calvo scheme in order to see how strongly the welfare implications of the Calvo scheme are influenced by the persistence of contracts older than ten periods. Wolman contracts provide an ad hoc way of capturing the notion that firms have the more to gain from re-optimizing their prices the longer prices have not been adjusted. Therefore, the adjustment probability should be increasing in the time since last adjustment.

Formally, every period a firm faces a given vector of probabilities $\alpha^p = (\alpha_1^p, \alpha_2^p, ..., \alpha_{J^p}^p)$ of receiving a signal allowing it to reset its product price, $P_t(z)$. The generic entry α_j^p denotes the probability that a firm that last changed its price in period $t - j$ is allowed to change its price in period t. Firms that do not receive the signal, carry on the prices posted in the last period and satisfy any demand at that price. Given the vector of adjustment probabilities α^p, firms compute the vector of probabilities $\phi^p = (\phi_1^p, \phi_2^p, ..., \phi_{J^p}^p)$ that the price set today will still be in place i periods from now. The relationship between the the vectors α^p and ϕ^p is outlined in Wolman (1999). Here, J^p indicates the maximum age of a price given the adjustment probabilities α^p.

The firm's price setting problem is:

$$\max_{P_t^*(z)} \mathrm{E}_t \sum_{i=0}^{J^p} \phi_i^p \beta^i \xi_{t+i} C_{t+i}^{-\sigma} \left\{ \tau_p \left[\frac{P_t^*(z)}{P_{t+i}} \right]^{1-\epsilon} Y_{t+i} - X_{t+i} \left[\frac{P_t^*(z)}{P_{t+i}} \right]^{-\epsilon} Y_{t+i} \right\}.$$

Here, τ_p is a sales subsidy suitably chosen to offset the steady state effects of monopolistic competition, $\tau_p = \epsilon/(\epsilon - 1)$. Defining the relative price of the firm's product as $p_t(z)^* \equiv P_t(z)^*/P_t$, the first-order condition for the firm's optimal price setting policy is:

$$p_t^*(z) = \frac{E_t \sum_{j=0}^{J^p-1} \phi_j^p \beta^j \xi_{t+j} C_{t+j}^{-\sigma} X_{t+j} \left(\pi_{t,t+j}\right)^{\epsilon} Y_{t+j}}{E_t \sum_{j=0}^{J^p-1} \phi_j^p \beta^j \xi_{t+j} C_{t+j}^{-\sigma} \left(\pi_{t,t+j}\right)^{\epsilon-1} Y_{t+j}}. \tag{7}$$

Here, $\pi_{t,t+j} \equiv \Pi_{k=1}^{j} \pi_{t+k}$ is the rate of inflation between periods t and $t + j$ (with $\pi_{t,t} \equiv 1$). From the price index, we obtain

$$1 = \left[\sum_{j=0}^{J^p-1} \omega_j^p \left(\frac{p_{t-j}^*}{\pi_{t-j,t}} \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}. \tag{8}$$

The households' wage setting problem is analogous. With a given probability α^w households, like firms, receive a signal each period allowing them to adjust their nominal wage contracts. Given the vector of adjustment probabilities, households maximize utility through choice of the wage subject to the demand curve for their type of labor. Let ϕ_j^w denote the probability that a wage set in period t is still in place in period $t + j$. The first-order condition for the wage can be expressed in terms of the relative wage $w_t(h) \equiv W_t(h)/W_t$ as:

$$(w_t(h)^*)^{1+\kappa\chi} = \frac{\kappa}{\tau_w(\kappa - 1)} \frac{E_t \sum_{j=0}^{J_w-1} \phi_j^w \beta^j \left(\pi_{t,t+j}^w\right)^{\kappa(1+\chi)} L_{t+j}^{1+\chi}}{E_t \sum_{j=0}^{J_w-1} \phi_j^w \beta^j \left(\pi_{t,t+j}^w\right)^{\kappa} L_{t+j} \xi_{t+j} C_{t+j}^{-\sigma} \frac{w_{t+j}^r}{\pi_{t,t+j}^w}}. \tag{9}$$

Here, $\pi^w_{t,t+j} \equiv \Pi^j_{k=1}\pi^w_{t+k}$ is the rate of wage inflation between periods t and $t+j$ (with $\pi^w_{t,t} \equiv 1$). As before, we assume that subsidies bring about an efficient steady state, i.e $\tau_w = \frac{\kappa}{\kappa-1}$. From the wage index, we obtain:

$$1 = \left[\sum_{j=0}^{J^w-1} \omega^w_j \left(\frac{w^*_{t-j}}{\pi^w_{t-j,t}}\right)^{1-\kappa}\right]^{\frac{1}{1-\kappa}}. \tag{10}$$

These optimality conditions for wage and price setting hold for all the sticky contracting schemes we consider. We calibrate the different schemes to have the same average age as four-period Taylor contracts. The average age of N-period Taylor contracts is $(N+1)/2$, i.e. 2.5 quarters for $N = 4$. The average age of Calvo contracts with an adjustment probability of α is α^{-1}, hence we set $\alpha = 0.4$. For truncated Calvo and the Wolman scheme, we refer to Wolman (1999) on how to compute the average age. Here we simply sketch the vector α for each scheme.[4]

mechanism	adjustment probability	maximum period
Calvo:	$\alpha_i = 0.4$ for all i	$J = \infty$
truncated Calvo:	$\alpha_i = 0.389$ for all $i < 10$, $\alpha_{10} = 1$	$J = 10$
Wolman	$\alpha_{i-1} < \alpha_i$ for $i = 2, ..., 9$, $\alpha_{10} = 1$	$J = 10$
Taylor	$\alpha = (0, 0, 0, 1)$	$J = 4.$

Table 1: Parameterization of pricing mechanisms

Our price and wage setting schemes thus differ in the age distribution of prices and wages around the average age of 2.5 quarters.[5]

Figure 1 plots the age distributions resulting from the four contracting schemes. The age distributions of Calvo and truncated Calvo contracts overlap strongly making them nearly indistinguishable in the graph.[6] The calibrated Wolman contracts look very similar to truncated Calvo contracts, but they place slightly less mass on age cohorts six through ten than truncated Calvo contracts. Finally, four-period Taylor contracts involve the familiar pattern of constant shares for cohorts one through four.

One can rank these contracting schemes according to the mass they place on the right tail of the age distribution, defined as the mass on ages 6-10. Among the schemes in

[4]Since we assume the same adjustment probabilities in wage and price setting we ignore the superscripts p and w for the vector α. For the Wolman scheme, the sequence of α_i is {0.26,0.30,0.35,0.45,0.5,0.55,0.6,0.7,0.9,1}

[5]Dixon and Kara (2006a) point out that the more traditional metric for ensuring comparability of different contracting schemes, namely requiring the same average frequency of price adjustment, biases results towards finding larger costs of Calvo over Taylor contracts in a steady state analysis

[6]Of course, the age distribution of Calvo contracts extends beyond the ten cohorts shown in the graph. They are neglected in the graph, the numerical analysis that follows considers the entire infinite tail of Calvo contracts.

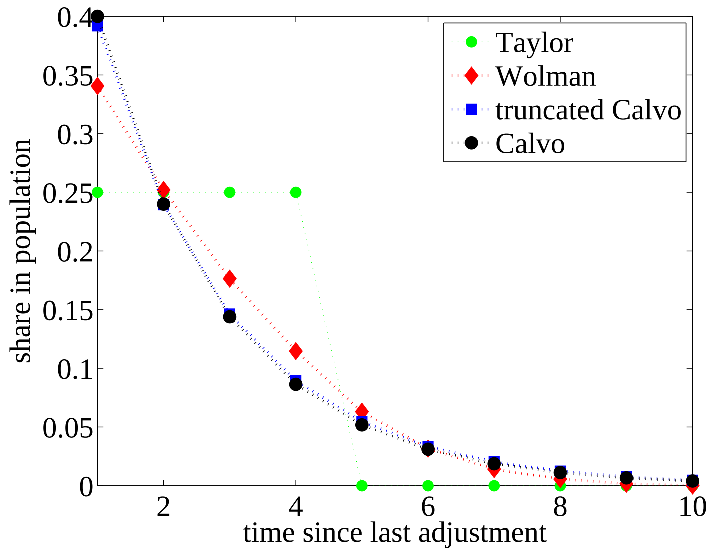

Figure 1: Age distribution of contracts

Figure 1, Calvo contracts have the largest tail mass, followed by truncated Calvo contracts, Wolman contracts, and Taylor contracts. One may conjecture that - for a given average age - having more mass in the right tail of the age distribution induces greater welfare costs of nominal rigidities, as firms and workers that have not adjusted their prices and wages for a long time are more likely to be further away from their optimal prices and wages. We investigate this conjecture numerically in the following sections.

3.2 Price and wage setting under sticky information

We build a N-period version of the sticky information scheme by Mankiw and Reis (2002). The arrival of new information is described by the same vector α as with sticky contracts. The generic entry α_j now denotes the probability that a firm or household that last updated its information set in period $t-j$ receives a signal to update its information set in period t. That setup gives rise to cohorts of agents indexed by when they last received an update of the information set. Agents in cohort j are free to change their posted wages or prices in any given period, but they do so using information sets that are outdated by j periods. We can therefore think of price and wage setting under sticky information as choosing an entire path for contract prices and wages applicable in future periods until another update of the information set occurs.

Let $P^*_{t,t-j}$ be the optimal price chosen by firms of cohort j conditional on the information set at time $t-j$, and $p^*_{t,t-j} = P^*_{t,t-j}/P_{t-j}$ the relative price in terms of the price level.

The first-order condition for optimal price setting is

$$p^*_{t,t-j} = \frac{E_{t-j}\,\xi_t C_t^{-\sigma} X_t \pi^{\epsilon}_{t-j,t} Y_t}{E_{t-j}\,\xi_t C_t^{-\sigma} \pi^{\epsilon-1}_{t-j,t} Y_t}. \tag{11}$$

Similarly, the optimal relative wage in terms of the aggregate wage index set by households of cohort j is

$$(w^*_{t,t-j})^{1+\kappa\chi} = \frac{E_{t-j}\,L_t^{1+\chi}\left(\pi^w_{t-j,t}\right)^{\kappa(1+\chi)}}{E_{t-j}\,\xi_t C_t^{-\sigma} L_t \left(\pi^w_{t-j,t}\right)^{\kappa-1} w^r_t} \tag{12}$$

Note that in (8) and (10) we must now replace p^*_{t-j} with $p^*_{t,t-j}$ and w^*_{t-j} with $w^*_{t,t-j}$.

4 Calibration

A time period is taken to be a quarter. The discount factor is set to the standard value $\beta = 0.99$. The markup is calibrated to 15% in both goods and labor markets, resulting in $\kappa = \epsilon = 7.66$. The labor share in production $1 - \alpha$ is set to the standard value 0.65. We assume a Frisch elasticity of labor supply of $1/3$ (implying $\chi = 3$), which is in line with most empirical estimates ranging between 0 and 0.5 as surveyed in Blundell and MaCurdy (1999). We set the coefficient of relative risk aversion σ to 2. This is a compromise between experimental evidence by Barsky, Juster, Kimball, and Shapiro (1997) who find a mean risk aversion of roughly 4 and the value of 1 commonly chosen in RBC models.

The monetary shock is assumed to be i.i.d. $m_t \sim \mathcal{N}(0, \sigma_m^2)$, while total factor productivity and the preference shock follow exogenous AR(1) processes:

$$\log A_t = \rho_a \log A_{t-1} + a_t, \quad a_t \sim \mathcal{N}(0, \sigma_a^2), \tag{13}$$

$$\log \xi_t = \rho_\xi \log \xi_{t-1} + g_t, \quad g_t \sim \mathcal{N}(0, \sigma_g^2). \tag{14}$$

We calibrate the stochastic process for technology similar to Prescott (1986). In line with the evidence in Smets and Wouters (2003), we assume a large serial correlation in the preference shock. Thus, we set $(\rho_a, \rho_\xi) = (0.95, 0.95)$ and $(\sigma_a, \sigma_\xi) = (0.008, 0.01)$. Following, Canzoneri, Cumby, and Diba (2007), the standard deviation of the monetary policy shock is set to $\sigma_m = 0.0025$.[7]

Since the welfare costs of nominal rigidities are sensitive to the monetary policy rule in place, we consider a variety of rules.

[7] With this calibration, the overall amount of volatility present in the model is roughly comparable to US data. For instance, the baseline calibration implies that the standard deviation of consumption with Calvo pricing ranges between 0.014 (for rule 1 below) and 0.034 (for rule 5 below). The average standard deviation across rules under the baseline calibration is 0.02 in the model. This is close to the volatility of HP filtered U.S. consumption in the postwar period reported by Lucas (2003).

rule	description	α_0	α_1	α_2	α_3
1:	response to inflation and gap, with inertia	0.5	1.5	0.75	0
2:	response to inflation only, with inertia	0	1.5	0.75	0
3:	response to inflation only, no inertia	0	1.5	0	0
4:	response to inflation and gap, no inertia	0.5	1.5	0	0
5:	price stability	0	100	0	0
6:	response to wage inflation and gap with inertia	0.5	0	0.75	1.5
7:	wage stability	0	0	0	100

Table 2: Parameterization of monetary policy rules

Rules 1 and 4 are variants of the interest rate rules suggested by Henderson and McKibbin (1993) and Taylor (1993). We allow for inertia as empirical studies commonly find that central banks smooth interest rates over time. Rules 2 and 4 have monetary policy respond moderately to price inflation alone, while rule 5 implements strict inflation targeting - the policy that is close to optimal in many models with price stickiness only. Rules 6 and 7 are analogous to rules 1 and 5, respectively, but monetary policy reacts to wage rather than price inflation. With nominal wage rigidities such rules seem a natural extension of rules responding to price inflation. In practice, central banks do not commonly target wage inflation explicitly, but they sometimes warn that wage pressures might cause a tightening of monetary policy and that wage moderation might be met with monetary easing, suggesting that they do pay attention to wage inflation.

5 Welfare costs of nominal rigidities

In this section, we compute the welfare costs of business cycle fluctuations stemming from nominal rigidities in wage and price setting. Following the linear-quadratic approach described in Woodford (2003a), we derive a welfare measure from the expected lifetime utility of a representative household whose instantaneous utility function is

$$\mathbb{W}_t \equiv \int_0^1 \mathbb{W}_t(h)dh. \tag{15}$$

Let $\mathbb{W}_t^*$ denote the instantaneous utility under flexible wages and prices. Our welfare measure of the cost of nominal rigidities is based on the difference between representative household's utility with nominal rigidities and without,

$$\mathbb{L} \equiv -\frac{1}{\bar{C}}\mathrm{E}\sum_{t=0}^{\infty}\beta^t\frac{\mathbb{W}_t - \mathbb{W}_t^*}{\bar{C}^{-\sigma}} \times 100 \tag{16}$$

where E denotes an unconditional expectation and $\bar{C}$ steady-state consumption. We interpret $\mathbb{L}$ as the discounted value of a permanent increase in steady-state consumption necessary to make agents as well off in a world with nominal rigidities as in a world with perfectly flexible wages and prices. For example, $\mathbb{L} = 2$ means that the representative household's consumption would have to increase by 2 percent of the steady state value in every period to make that household equally well off as in a world with no nominal rigidities. Alternatively, the representative household would have to receive a one-time compensation of 200 percent of his quarterly steady state consumption to be equally well off.[8] Note that $\mathbb{W}_t$ and, therefore, $\mathbb{L}$, generally depend on the monetary policy rule, while $\mathbb{W}_t^*$ does not. The criterion $\mathbb{L}$ can be approximated up to second order by the following weighted sum of second moments:

$$\mathbb{L} \sim \mathrm{E}\sum_{t=0}^{\infty}\beta^t\left[\tilde{\lambda}_0\sum_{j=0}^{J^p-1}\omega_j^p\left(\widehat{p^{\diamond}}_{t-j}\right)^2+\tilde{\lambda}_1\left(\hat{Y}_t-\hat{Y}_t^*\right)^2+\tilde{\lambda}_2\sum_{j=0}^{J^w-1}\omega_j^w\left(\widehat{w^{\diamond}}_{t-j}\right)^2\right], \tag{17}$$

$$\text{with: } \tilde{\lambda}_0 = \frac{1}{2}\frac{\epsilon}{\Phi}, \quad \tilde{\lambda}_1 = \frac{1}{2}\left(\frac{\chi+\alpha}{1-\alpha}+\sigma\right), \quad \tilde{\lambda}_2 = \frac{1}{2}(1-\alpha)(\kappa^{-1}+\chi)\kappa^2.$$

Here, $\widehat{p^{\diamond}}_{t-j} \equiv \widehat{P^*}_{t-j} - \widehat{P}_t$ and similarly for $\widehat{w^{\diamond}}_{t-j}$. Since this loss function is free of first moments, it can be accurately (up to second-order) evaluated by considering a linear approximation to the model's equilibrium conditions presented in the Appendix. The term Φ is unity with an economy wide rental market for capital but will differ when we consider firm specific capital in a robustness check later on. For Calvo (1983) contracts, $J^P = J^W = \infty$ and (17) collapses into the well-known welfare function:

$$\mathbb{L} \sim \mathrm{E}\sum_{t=0}^{\infty}\beta^t\left[\lambda_0\hat{\pi}_t^2+\lambda_1\left(\hat{Y}_t-\hat{Y}_t^*\right)^2+\lambda_2\widehat{\pi^w}_t^2\right]. \tag{18}$$

Here, the weights are given by

$$\lambda_0 = \frac{\epsilon\theta}{2(1-\theta)(1-\theta\beta)\Phi}, \quad \lambda_1 = \frac{1}{2}\left(\frac{\chi+\alpha}{1-\alpha}+\sigma\right), \quad \lambda_2 = \frac{\theta_w\kappa^2(1-\alpha)(\kappa^{-1}+\chi)}{2(1-\theta_w)(1-\theta_w\beta)}.$$

We solve for the rational expectations solution of the log-linearized equilibrium conditions (see section 7.1 in the appendix) using a standard numerical algorithm and compute the unconditional variances in the loss function.

5.1 Welfare costs of sticky contracting schemes

Table 3 displays the welfare cost of nominal rigidities for the baseline parameterization of our model, given the alternative contracting schemes and policy rules defined above.

[8] With $\beta = 0.99$, one time compensation equals 100 times the compensation in every period.

rule	$\mathbb{L}$ (Calvo)	$\mathbb{L}$ (tr. Calvo)	$\mathbb{L}$ (Wolman)	$\mathbb{L}$ (Taylor)
1	3.408	3.305	2.934	2.033
2	0.313	0.288	0.227	0.135
3	0.561	0.505	0.384	0.203
4	4.437	4.319	3.898	2.756
5	0.304	0.304	0.286	0.240
6	2.752	2.675	2.394	1.703
7	0.024	0.024	0.022	0.018

Table 3: Welfare costs of nominal rigidities across contracting schemes and monetary policy rules, baseline calibration.

The results show, first, that the welfare costs of nominal rigidities under the current parameterization can be substantial. A household in a world with nominal rigidities would require a compensation of up to 4.44 percent of steady state consumption to be equally well off as in a world with fully flexible prices and wages. For a given monetary policy rule, Calvo contracts generate the largest welfare costs, followed by truncated Calvo contracts, Wolman contracts, and Taylor contracts. The differences between the Calvo and the truncated Calvo schemes are typically small, suggesting that getting rid of all contracts older than 10 periods does not yield a substantial welfare gain. The differences between the Calvo scheme and the Wolman scheme are more significant, ranging between six and 46 percent of the welfare cost generated by Wolman contracts. Finally, Taylor contracts yield the smallest welfare cost of all four schemes. Calvo contracts can involve welfare costs that are up to 2.76 times bigger than the costs associated with Taylor contracts. This supports our conjecture that the welfare costs of nominal rigidities increase in the mass the age distribution places on contracts older than five periods.

Next, the table indicates that the welfare costs of nominal rigidities are highly dependent on the specific monetary policy rule. This is in line with Canzoneri, Cumby, and Diba (2007) and Levin, Onatski, Williams, and Williams (2006) who also find an important influence of monetary policy on welfare in sticky price and wage models. Rules 1, 4, and 6, which react to the output gap, perform most poorly under all price and wage setting schemes. To understand this, recall that the gap is defined as deviations of output from the steady state. Since potential output is highly variable due to technology and preference shocks, tightening policy in response to deviations of output from steady state (instead of output from potential) is a bad policy. Comparing rules 1 and 4 shows that adding inertia to a policy rule reacting to the output gap improves its performance as suggested by Woodford (2003b). Comparing rules 1 and 6 shows that replacing price with wage inflation in the Taylor rule improves the performance of monetary policy significantly. As in Canzoneri, Cumby, and Diba (2007), the wage setting distortion matters more in welfare terms than the price setting distortion. Finally, the pure wage- stability rule 7 reduces the welfare cost of nominal rigidities almost to zero, and this is the dominant policy rule in this setting.

To see why targeting wage inflation does better than targeting price inflation in this model, consider the weights on price and wage dispersion in the welfare function (17), λ_0 and λ_1, respectively. The parameter ϵ, which reflects the market power of intermediate goods firms in their markets, enters λ_0 linearly, while the parameter κ, which reflects households' market power in the labor market, enters λ_1 quadratically. Thus, unless the labor supply elasticity $1/\chi$ is very large, or κ is very small relative to ϵ, the welfare weight on wage dispersion is likely to be large compared to the welfare weight on price dispersion and this generates a preference for keeping the former small. Figure 6 in the appendix illustrates this point more generally and shows that, in our calibration, price stability dominates wage stability only for very low values of χ and κ.

While the level of welfare costs associated with a particular monetary policy rule depends strongly on the assumed wage and price setting mechanism, the welfare *ranking* of the monetary policy rules in Table 3 does not. Under all mechanisms, rule 7 performs best and rule 4 worst. There is only one switching of ranks in the table, namely between rule 5 which is second best under Calvo pricing and third under all alternatives, and rule 2, which is third under Calvo pricing and second otherwise. Apart from this minor difference, the table clearly indicates that rules performing relatively well in one environment will do so in others as well, and rules performing relatively poorly in one environment will do so in others. In particular, wage stability is the optimal rule for all the contracting schemes considered.

To see how much these results dependent on the specific calibration of the model, we draw $n = 10,000$ combinations of the structural parameters from intervals taken from Pappa (2005) with some adjustments. These intervals reflect the range of values typically used in the literature. The discount factor is fixed at the standard value $\beta = 0.99$. Since empirical studies do not report an interest rate rule that responds to wage inflation, we set the interest rate rule parameter α_3 to zero. The remaining parameters are assumed to be uniformly distributed in the intervals shown in Table 4. For each draw of the structural parameters we compute the welfare costs of nominal rigidities under the different contracting schemes as before. We then compute the ratio of the welfare costs under each of the other schemes relative to Calvo pricing for each of the n draws.[9]

[9]One could take this approach one step further and estimate the parameters separately for each model and then draw from the posterior parameter distribution. However, evidence in Paustian and Pytlarczyk (2005) as well as Laforte (2007) suggests that most structural parameters are estimated at similar values across different contracting schemes.

symbol	parameter name	support
β	discount factor	0.99
α_3	response to wage inflation in Taylor rule	0
ϵ	elasticity in goods bundler	[6.000, 11.00]
κ	elasticity in labor bundler	[6.000, 11.00]
σ	risk aversion coefficient	[1.000, 4.000]
χ	inverse Frisch elasticity of labor supply	[1.000, 4.000]
α	capital share in production function	[0.300, 0.400]
α_0	response to output gap in Taylor rule	[0.000, 0.500]
α_1	response to inflation in Taylor rule	[1.250, 2.000]
α_2	inertia in Taylor rule	[0.000, 0.750]
ρ_a	persistence of productivity process	[0.500, 0.950]
ρ_ξ	persistence in preference process	[0.500, 0.950]
σ_a	stdv. of innovation into productivity	[0.002, 0.020]
σ_g	stdv. of innovation into preference	[0.002, 0.020]
σ_m	stdv. of monetary shock	[0.002, 0.020]

Table 4: Support of uniform parameter distribution for robustness analysis.

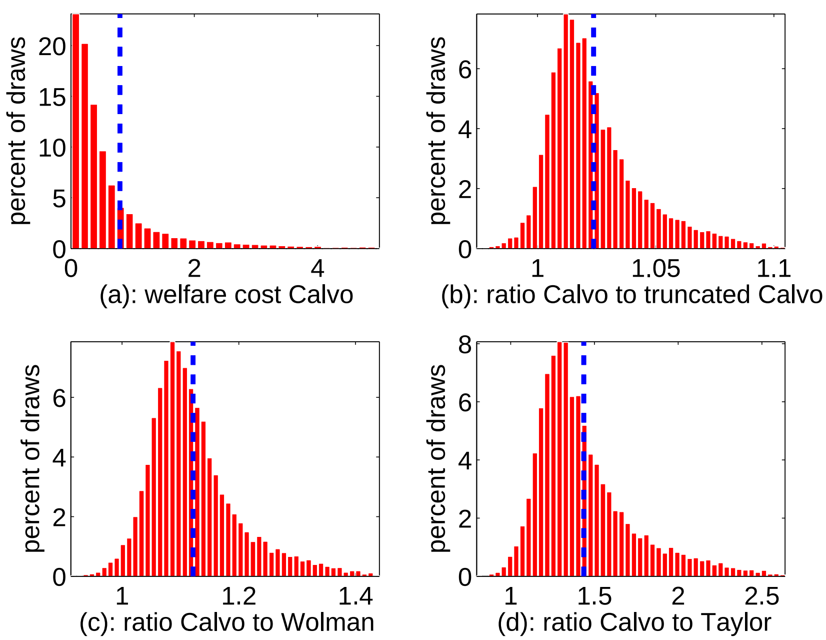

Figure 2: Distribution of welfare costs. Dashed line denotes the mean of the distribution.

The histograms in Figure 2 summarize the information from this sensitivity analysis.

Panel (a) shows the histogram of the welfare costs of nominal rigidities in the Calvo model. The mean cost is 0.79 per cent with Calvo contracts. Panels (b)-(d) show the distributions of the relative welfare costs under truncated Calvo, Wolman and Taylor compared to Calvo contracts for each draw of parameters. For all but very small fractions of draws, these ratios are above unity. Hence, the finding that Calvo contracts involve the highest welfare costs is robust across the broad range of parameters that we consider. Based on the mean of the distribution, Calvo contracts involve 2 % larger costs than truncated Calvo contracts, 12% larger costs than Wolman contracts and 43% larger costs than Taylor contracts. This suggests that the welfare ranking of contracting schemes is robust to reasonable parameter variations. Section 7.3 in the appendix documents that these findings are also robust to making the variance of one of the three shocks hitting the economy much larger than the variances of the others. Hence, our conjecture that placing more mass in the right tail of the age distribution of contracts increases the welfare costs of nominal rigidities is largely confirmed.

It is worth noting that the welfare costs of nominal rigidities are linear in the variances of all shocks. Therefore, the panels (b) - (d) in Figure 2 have an alternative interpretation. They tell us how much larger the variance of structural shocks could be in a world with a particular contracting scheme to yield the same welfare costs of nominal rigidities as Calvo contracts. For example, based on the mean, the variance of shocks can be up to 43% larger for the model with Taylor contracts to have smaller welfare costs than Calvo contracts.

We perform a similar parameter sensitivity analysis regarding the welfare ranking of our monetary policy rules across the different contracting schemes. Here, we draw 1000 combinations of the structural parameters from the same intervals as before, but holding the parameters of the monetary policy rules fixed. Next, we constructed the rank correlation coefficients between the welfare rankings of rules 1 - 7 across all pairs of contracting schemes.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	0.98	0.97	0.93
tr. Calvo	0.98	1.00	0.99	0.95
Wolman	0.97	0.99	1.00	0.97
Taylor	0.93	0.95	0.97	1.00

Table 5: Spearman rank correlation coefficients for the welfare ranking of monetary policy rules

Table 5 reports the average rank correlation coefficient across the 1000 draws. The table shows that the welfare ranking of monetary policy rules across the four contracting schemes is highly robust to variations in the other parameters. The rank correlations are 0.93 or larger for all pairs of schemes. Thus, our result that the relative performance monetary policy rules is highly stable across alternative contracting schemes does not depend on the parameterization of the model.

5.1.1 Real rigidities in the form of immobile capital

So far we have assumed that capital is freely mobile across firms within each period. Danthine and Donaldson (2002), Woodford (2003a, p.166) and others have argued that this is unrealistic in view of the costs of relocating existing physical capital. [10] To explore this issue, we check how the welfare costs of nominal rigidities across the considered schemes depend on the mobility of capital. For this purpose, we assume that capital is fixed at the firm level. The problem of the firm now is to choose its optimal nominal price $P_t^*(z)$ subject to the demand curve and the production function to maximize

$$\max_{P_t^*(z)} \mathrm{E}_t \sum_{i=0}^{J^p} \phi_{t+i}^p \beta^i C_{t+i}^{-\sigma} \left\{ \tau_p \left[\frac{P_t^*(z)}{P_{t+i}} \right]^{1-\epsilon} Y_{t+i} - Z_{t+i} K(z) - w_{t+i}^r L_{t+i}(z) \right\}.$$

The first-order condition for this problem can be expressed as:

$$\mathrm{E}_t \sum_{i=0}^{J^p} \phi_{t+i}^p \beta^i C_{t+i}^{-\sigma} \left\{ \tau_p (1-\epsilon) \left[\frac{P_t^*}{P_{t+i}} \right]^{1-\epsilon} Y_{t+i} + \frac{\epsilon}{1-\alpha} w_{t+i}^r L_{t+i}(z) \right\} = 0. \quad (19)$$

Linearizing the price setting block (see appendix) results in a Phillips curve whose slope is flatter than in the case of mobile capital. To see why, consider the problem of a firm that receives a signal to change its price. By setting a lower price than the firms maintaining their prices, it can attract additional demand. But with firm specific capital, marginal cost depends on the firms' own level of production rather than the aggregate production level as in the case with mobile capital. Therefore, the firm will choose a relative price that deviates less from unity than in the case where marginal cost depends aggregate output. As a result the variance of price inflation is smaller with immobile capital.[11]

At the same time, the weight on the dispersion of relative prices in the welfare function increases. The reason for this is that, with immobile capital, a given dispersion in relative quantities results in a much bigger dispersion of labor across firms. With capital fixed at the firm level, the firm can adjust production only by changing its labor input. Since labor has decreasing marginal product in production at the level of the individual firm, the dispersion of labor across firms is welfare reducing. Since the dispersion of labor across firms is positively correlated with the rate of price inflation, a given amount of inflation variability is now roughly five times more costly in welfare terms than with mobile capital for our benchmark values of α and ϵ.

[10] Furthermore, Eichenbaum and Fischer (2004) show that departing from the assumption of perfect capital mobility is necessary to reconcile the Calvo (1983) model with the data. Sveen and Weinke (2004) further discuss the implications of modeling capital for the equilibrium dynamics in sticky prices models. See Levin, Lopez-Salido, and Yun (2007) regarding the implications of strategic complementarities on optimal monetary policy

[11] See Kimball (1995) for a discussion of assumption on factor markets on price setting and Ball and Romer (1990) for the seminal paper on real rigidities.

rule	$\mathbb{L}$ (Calvo)	$\mathbb{L}$ (tr. Calvo)	$\mathbb{L}$ (Wolman)	$\mathbb{L}$ (Taylor)
1	3.650	3.566	3.231	2.332
2	0.354	0.326	0.260	0.159
3	0.587	0.532	0.413	0.227
4	4.598	4.518	4.179	3.105
5	0.291	0.290	0.269	0.218
6	3.300	3.225	2.920	2.126
7	0.041	0.040	0.037	0.029

Table 6: Welfare costs with immobile capital.

Table 6 displays the welfare costs of nominal rigidities for the case of immobile capital. Whether we model capital as fixed at the firm level or assume a rental market does not have a large effect on the welfare cost for the benchmark calibration of this model. The largest welfare costs now reach up to 4.6 percent of consumption. Except for the case of strict inflation targeting (rule 5), the welfare costs of nominal rigidities are larger with immobile than with mobile capital, though the differences are moderate. As before, we find that, for a given monetary policy rule, Calvo contracts are associated with the largest welfare costs, followed by truncated Calvo contracts, Wolman contracts and Taylor contracts. Again as before, we find that the welfare ranking of monetary policy rules is the same under the alternative price and wage setting mechanisms with the sole exception that rule 5 switches from second to third best and rule 2 from third to second best as we move from truncated Calvo to Wolman contracts.

To check for robustness to changes in the parameterization, we perform the same experiments as before. The histograms in figure 3 indicate that the distribution of welfare costs under Calvo contracts is similar to the baseline case. The mean welfare cost associated with Calvo contracts is 0.74. Furthermore, the histograms of the relative welfare costs associated with the other price and wage setting mechanisms show that, again, Calvo contracts dominate the alternatives only in a very small fraction of the parameter draws. The mean ratios are 1.02 for truncated Calvo contracts, 1.09 for Wolman contracts, and 1.29 for Taylor contracts.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	1.00	0.98	0.94
tr. Calvo	1.00	1.00	0.98	0.94
Wolman	0.98	0.98	1.00	0.97
Taylor	0.94	0.94	0.97	1.00

Table 7: Spearman rank correlation coefficients for the welfare ranking of monetary policy rules

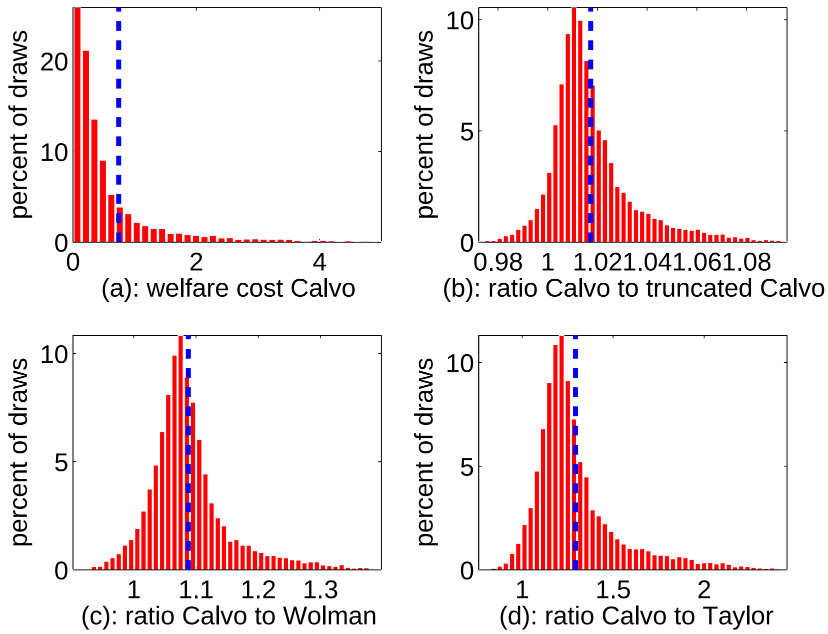

Figure 3: Distribution of welfare costs with immobile capital. Dashed line denotes the mean of the distribution.

Table 7 shows the Spearman rank correlations for the alternative monetary policy rules. As before, we find that these rankings are highly stable across alternative price and wage setting schemes.

5.1.2 A sophisticated output gap

Canzoneri, Cumby, and Diba (2007) show that, with Calvo pricing, the welfare costs of nominal rigidities depend on the definition of the output gap in the Taylor rule. In practice, central banks often react to deviations of output from a long run measure of potential output. This output gap concept is approximated by the deviation of output from its steady state in our analysis so far. However, the definition of the output gap implied by our welfare theoretic loss function is the gap between actual output and output under flexible prices and wages. The difference between these two measures of the gap is that the latter concept recognizes that potential output reacts to current shocks hitting the economy, while the former does not. In this section, we analyze the welfare costs of nominal rigidities associated with alternative price and wage setting schemes assuming that the central bank can observe and react to this more sophisticated measure of the output gap. Note that we return to the case of mobile capital.

rule	$\mathbb{L}$ (Calvo)	$\mathbb{L}$ (tr. Calvo)	$\mathbb{L}$ (Wolman)	$\mathbb{L}$ (Taylor)
1	0.151	0.146	0.130	0.092
2	0.313	0.288	0.227	0.135
3	0.561	0.505	0.384	0.203
4	0.227	0.222	0.200	0.141
5	0.304	0.304	0.286	0.240
6	0.071	0.070	0.065	0.052
7	0.024	0.024	0.022	0.018

Table 8: Welfare costs of nominal rigidities with alternative output gap.

Table 8 shows, first, that the welfare costs of nominal rigidities are considerably smaller in this case. The largest welfare cost is associated with Calvo contracts and amounts to 0.56% of consumption. Yet, again, we find that, for a given policy rule, Calvo contracts are associated with the largest welfare costs, followed by truncated Calvo contracts, Wolman contracts, and Taylor contracts. There are still differences in the performance of the monetary policy rules, but they are less pronounced than in the case where the central bank responds to the more pragmatic measure of the output gap. Note that policy rules responding only to price inflation (rules 3 and 5) perform least well in this case. Responding to the sophisticated measure of the output gap in addition to price inflation improves the performance of monetary policy, as does adding inertia (rule 4 is better than rule 5 and rule 1 is better than rule 2) under all price and wage setting schemes. Strict wage-inflation targeting (rule 7) dominates the other rules under all price and wage setting schemes. Finally, we note that the ranking of monetary policy rules is less stable than before. Specifically, rules 2 - 5 switch ranks as we move from Wolman to Taylor contracts. Thus, a central bank that is able to observe and respond to the sophisticated output gap would like to know more about the contract scheme prevailing in its economy to pick to the best policy rule. At the same, however, the differences in performance between these rules are less pronounced than when the central bank uses the cruder measure of the output gap. That is, such information is less valuable under these circumstances.

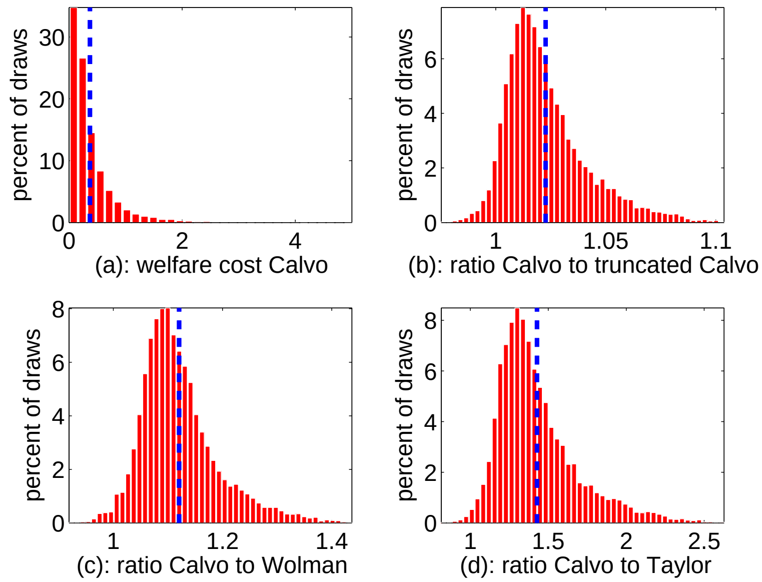

Figure 4: Distribution of welfare costs with sophisticated definition of output gap. Dashed line denotes the mean of the distribution.

Repeating the simulation exercise as before, figure 4 shows the distribution of the welfare costs associated with Calvo pricing and the distribution of the relative welfare costs associated with the other wage and price setting schemes with the sophisticated definition of the output gap. Comparing Panel (a) in this figure to the corresponding panel in Figure 2 confirms the result in Canzoneri, Cumby, and Diba (2007) that level the welfare costs is lower if the central bank reacts to the welfare relevant gap measure. The mean welfare cost with Calvo contracts is now only 0.37 vs 0.79 percent with the gap defined as deviation from steady state. The welfare costs of other schemes *relative* to Calvo are largely the same as with the alternative output gap definition. Based on the mean of the distribution, Calvo contracts imply 2% higher costs than truncated Calvo, 12% higher costs than Wolman and 42% higher costs than Taylor contracts. Therefore, we conclude that our analysis of the relative welfare costs of nominal rigidities does not depend on how the output gap is defined.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	1.00	0.99	0.97
tr. Calvo	1.00	1.00	0.99	0.97
Wolman	0.99	0.99	1.00	0.98
Taylor	0.97	0.97	0.98	1.00

Table 9: Spearman rank correlation coefficients.

Table 9 reports the Spearman rank correlations for the alternative monetary policy rules. Here we find almost perfect correlations across all parameter draws. As before, we find that the ranking of monetary policy rules is very robust to changes in the price and wage setting mechanism.

5.2 Welfare costs of sticky information schemes

The previous subsection found that contracting schemes with a larger mass in the tail of the age distribution involve higher welfare costs of nominal rigidities. One may suspect that a similar result holds when nominal rigidities arise because of sticky information. Little is known empirically about the age distribution of information sets for wage and price setters in Mankiw and Reis (2002) type models. Therefore, one can again ask whether it matters for the welfare costs of nominal rigidities in sticky information models what age distribution of information sets is assumed.

This subsection explores welfare implications of different age distributions as depicted in Figure 1 which now refer to the age of the information sets. The loss function for the sticky information model is again of the form (17), where $\widehat{p^*}_{t-j}$ is now replaced by $\widehat{p^*}_{t,t-j}$ and $\widehat{w^*}_{t-j}$ by $\widehat{w^*}_{t,t-j}$, and similar substitutions are made for the wage and price indices. Table 10 displays the welfare losses associated with different monetary policy rules and different assumptions about the arrival rates of new information.[12]

rule	$\mathbb{L}$ (Calvo)	$\mathbb{L}$ (tr. Calvo)	$\mathbb{L}$ (Wolman)	$\mathbb{L}$ (Taylor)
1	0.583	0.427	0.310	0.126
2	0.073	0.065	0.055	0.037
3	0.046	0.035	0.025	0.017
4	0.450	0.285	0.176	0.048
5	0.288	0.285	0.268	0.222
6	0.613	0.485	0.378	0.184
7	0.024	0.024	0.023	0.019

Table 10: Welfare costs of nominal rigidities in sticky information model

Table 10 shows that the welfare costs associated with price and wage setting under sticky information are considerably smaller than with sticky contracts. The largest welfare costs are now 0.6 percent of consumption. As before, we find that, for a given monetary policy rule, the Calvo scheme is associated with the largest welfare costs, followed by the truncated Calvo, the Wolman and the Taylor scheme.

[12]For computational reasons, we approximate the Calvo type sticky information model by truncating the geometric decay at a very high value, since we cannot write the Phillipscurve recursively as with sticky prices. Here, we follow Trabandt (2005) and truncate at period $J = 25$. With this truncation point, the mass of information sets that we ignore is practically zero.

Monetary policy rules reacting to the output gap in addition to inflation generate welfare losses that are between 3.5 and 8 times larger than policy rules reacting to price inflation only. Strict wage-inflation targeting (rule 7) remains the dominant policy rule under the Calvo, truncated Calvo and Wolman schemes, and is second best under the Taylor scheme. Given the latter, moderate price-inflation targeting with no inertia (rule 3) performs best, but its advantage over strict wage inflation targeting is minor. In contrast, the performance of strict price-inflation targeting (rule 5) is mediocre under the Calvo, truncated Calvo and Wolman schemes, and the worst under the Taylor scheme. Compared with the results of sections 5.1.1. and 5.1.2., where the central bank reacts to the same output gap as here and rule 5 always performed relatively well, this suggests that the proper design of a monetary policy rule depends more on knowing whether sticky contracts or sticky information is the paradigm properly describing price and wage setting in an economy, than knowing which age distribution contracts have. Table 10 indicates that the welfare ranking of the policy rules is less stable across price and wage setting schemes than in the case of sticky contracts, as several rules switch ranks when we compare the Wolman and the Taylor scheme. Still, the three best rules (rules 2, 3, and 7) dominate the others under all sticky information schemes.

We again undertake a parameter sensitivity analysis and draw $N = 1,000$ times from the prior distribution of structural parameters.[13]

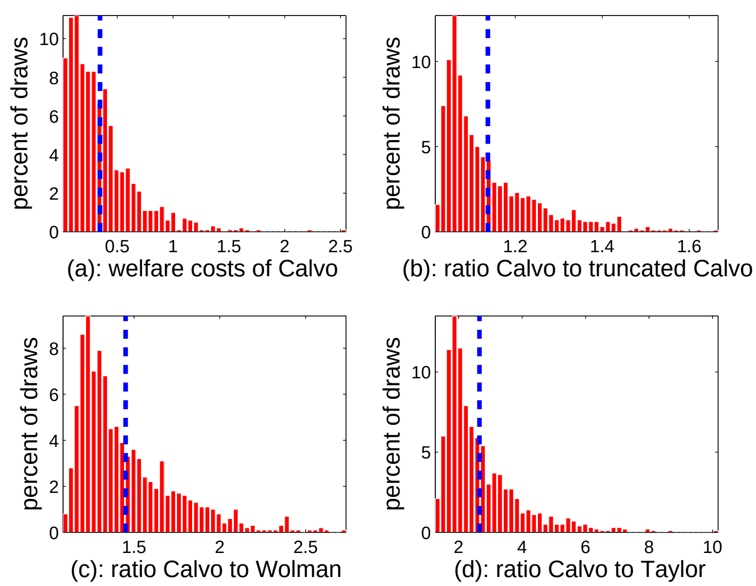

Figure 5: Distribution of welfare costs, sticky information. Dashed line denotes the mean.

With Calvo style updating of information sets, the average welfare cost of nominal

[13]We only draw 1,000 instead of 10,000 parameters, because sticky information models with a high number of lags are time consuming to solve with standard methods.

rigidities is 0.34 percent. Figure 5 shows that the welfare ranking is robust across parameter variations. The ratio of welfare costs in the truncated Calvo model relative to the Wolman model and relative to the Taylor model is above unity for all of the 1,000 draws. Based on the mean ratio, Calvo updating involves 13 percent higher costs than truncated Calvo type updating, 45 percent higher costs than Wolman type updating, and 165 percent higher costs than Taylor type updating. Thus, our finding that updating schemes that places more mass in the tail of age distribution involve larger welfare costs is also robust to reasonable parameter variations.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	0.97	0.91	0.77
tr. Calvo	0.97	1.00	0.95	0.82
Wolman	0.91	0.95	1.00	0.89
Taylor	0.77	0.82	0.89	1.00

Table 11: Spearman rank correlation coefficient in the sticky information model.

Finally, Table 11 indicates that, with sticky information, the ranking of monetary policy rules is less stable across price and wage setting schemes than with sticky contracts. This is especially true comparing the Taylor scheme with all others. Thus, a central bank knowing that it operates in an environment with sticky information rather than sticky contracts would want to know more about the frequency of information updates in the economy than a central bank operating in sticky-contracts environment would want to know about the frequency of contractual wage and price changes.

6 Conclusion

Given the scarcity of pertinent empirical information, there is little agreement among macroeconomists today over how to model nominal rigidities appropriately. In this paper, we have explored the welfare costs associated with different price and wage setting mechanisms in a standard New Keynesian, dynamic general equilibrium model to see how important this uncertainty is for the analysis of the welfare costs of nominal rigidities and the design of optimal monetary policy rules.

We find that the welfare costs of nominal rigidities can vary substantially across different price and wage setting schemes and across monetary policy rules. Qualitative statements about the welfare costs associated with different mechanisms and rules, however, are strongly robust to changes in the parametrization and specification of the model. For given monetary policy rules and a given average age of contracts in the economy, the age distribution of contractual wages and prices matters. The more mass this distribution places on older contracts, the larger are the welfare costs of nominal rigidities. A similar result holds for the sticky-information scheme proposed by Mankiw and Reis (2002). For either sticky contracts or sticky information environments, welfare rankings of monetary policy rules are strongly robust to changes in the underlying mechanisms generating sticky prices and wages. This suggests that the assessment of alternative monetary policy rules does not depend much on the particular choice of mechanism generating nominal rigidities, and that this choice can be driven largely by considerations of modeling convenience.

However, the ranking of monetary policy rules turns out to be different under sticky contracts than under sticky information price and wage setting. Thus, for the evaluation of alternative monetary policy rules, the difference between these two paradigms matters more than the differences between the different price and wage setting and information updating schemes. More research is necessary to identify which of these paradigms is more relevant empirically.

7 Appendix

7.1 Loglinearized equilibrium conditions

This appendix collects the loglinearized equilibrium conditions used to solve the model. The following conditions are common across contracting schemes. They are loglinearized version of the corresponding equations in the main text. In addition, equation (23) is an identity linking the real wage growth to wage and price inflation. As in Erceg, Henderson, and Levin (2000), equation (24) links real marginal cost to the output gap and the gap between the marginal rate of substation and the real wage.

$$\widehat{Y}_t = E_t\widehat{Y}_{t+1} - E_t\sigma^{-1}\left(\widehat{R}^n_t - \widehat{\pi}_{t+1} + \hat{\xi}_{t+1} - \hat{\xi}_t\right), \tag{20}$$

$$\widehat{Y}_t = \widehat{A}_t + (1-\alpha)\widehat{L}_t, \tag{21}$$

$$\widehat{w^r}_t = \widehat{X}_t + \widehat{A}_t - \alpha\widehat{L}_t, \tag{22}$$

$$\widehat{w^r}_t = \widehat{w^r}_{t-1} + \widehat{\pi^w}_t - \widehat{\pi}_t, \tag{23}$$

$$\widehat{X}_t = \left[\frac{\chi+\alpha}{1-\alpha} + \sigma\right]\left(\widehat{Y}_t - \widehat{Y^*}_t\right) - \left[\chi\widehat{L}_t + \sigma\widehat{Y}_t - \hat{\xi}_t - \widehat{w^r}_t\right], \tag{24}$$

$$\hat{R}^n_t = (1-\alpha_2)\alpha_0\left(\hat{Y}_t - \hat{Y}^*_t\right) + (1-\alpha_2)\alpha_1\hat{\pi}_t + \alpha_2\hat{R}^n_{t-1} + v_t. \tag{25}$$

Calvo contracts

With Calvo contracts, the following two equations close the model.

$$\widehat{\pi^w}_t = \frac{(1-\theta_w)(1-\beta\theta_w)}{\theta_w}\widehat{\mu}_t + \beta \mathrm{E}_t\widehat{\pi^w}_{t+1}, \tag{26}$$

$$\widehat{\pi}_t = \frac{(1-\theta)(1-\beta\theta)}{\theta}\Phi\widehat{X}_t + \theta\mathrm{E}_t\widehat{\pi}_{t+1} \tag{27}$$

Here, $\hat{\mu}_t \equiv (\chi\hat{L}_t + \sigma\hat{C}_t - \hat{\xi}_t - \hat{w}^r_t)/(1+\kappa\chi)$ is proportional to the gap between the marginal rate of substitution and the real wage. Furthermore, $\Phi \equiv 1$ for mobile capital and $\Phi \equiv \frac{(1-\alpha)}{(1-\alpha+\alpha\epsilon)}$ for firm specific capital.

Wolman contracts

The probability that a price readjusted today is still in place j periods from now is given by $\phi^p_j = \omega^p_j/\omega^p_0$. To induce stationarity, we express the optimal reset price $\hat{P}^*_t$ relative to the aggregate price level, i.e. $\hat{p}^*_t \equiv \hat{P}^*_t - \hat{P}_t$. Let ν_p be defined as $\nu_p \equiv \sum_{j=0}^{J-1}\beta^j\omega^p_j/\omega^p_0$. The optimal reset price is given by

$$\hat{p}^*_t = \Phi\frac{\hat{X}_t}{\nu_p} + \mathbb{E}_t\sum_{j=1}^{J-1}\frac{\beta^j\omega^p_j}{\omega^p_0\nu_p}\left[\Phi\hat{X}_{t+j} + \sum_{k=1}^{j}\hat{\pi}_{t+k}\right] \tag{28}$$

Here, Φ is defined as with Calvo contracts. From the price index, we have:

$$\hat{\pi}_t = \sum_{j=0}^{J-1} \frac{\omega_j^p}{1-\omega_0^p} \hat{p}_{t-j}^* - \sum_{j=2}^{J-1} \frac{\omega_j^p}{1-\omega_0^p} \left[\sum_{k=1}^{j-1} \hat{\pi}_{t-k} \right] \tag{29}$$

The wage setting condition is log-linearized as:

$$\hat{w}_t^* = \frac{\hat{\mu}_t}{\nu_w} + \mathbb{E}_t \sum_{j=1}^{J-1} \frac{\beta^j \omega_j^w}{\omega_0^w \nu_w} \left[\hat{\mu}_{t+j} + \sum_{k=1}^{j} \hat{\pi}_{t+k}^w \right] \tag{30}$$

The driving variable $\hat{\mu}_t$ is defined in the same way as under Calvo pricing. Here, ω_j^w denote the shares of wage setters that last updated their wages j periods ago and ν_w is defined as $\nu_w \equiv \sum_{j=0}^{J^p-1} \beta^j \omega_j^w / \omega_0^w$. From the wage index, we have:

$$\hat{\pi}_t^w = \sum_{j=0}^{J-1} \frac{\omega_j^w}{1-\omega_0^w} \hat{w}_{t-j}^* - \sum_{j=2}^{J-1} \frac{\omega_j^w}{1-\omega_0^w} \left[\sum_{k=1}^{j-1} \hat{\pi}_{t-k}^w \right] \tag{31}$$

Sticky information

Let ω_j^p denote the fraction of price setters that use information sets outdated by j periods and ω_j^w the corresponding fraction for wage setters. We define the log-linearized optimality conditions in terms of stationary variables $\hat{w}_{t,t-j}^* \equiv \hat{W}_{t,t-j}^* - \hat{W}_{t-j}$ and $\hat{p}_{t,t-j}^* \equiv \hat{P}_{t,t-j}^* - \hat{P}_{t-j}$:

$$\hat{w}_{t,t-j}^* = \mathbb{E}_{t-j} \left[\sum_{k=0}^{j-1} \hat{\pi}_{t-k}^w + \hat{\mu}_t \right], \qquad \hat{p}_{t,t-j}^* = \mathbb{E}_{t-j} \left[\sum_{k=0}^{j-1} \hat{\pi}_{t-k} + \hat{X}_t \right]. \tag{32}$$

The log-linearized price and wage indices are given by:

$$\hat{\pi}_t = \sum_{j=0}^{J-1} \frac{\omega_j^p}{1-\omega_0^p} \hat{p}_{t,t-j}^* - \sum_{j=2}^{J-1} \frac{\omega_j^p}{1-\omega_0^p} \left[\sum_{k=1}^{j-1} \hat{\pi}_{t-k} \right] \tag{33}$$

$$\hat{\pi}_t^w = \sum_{j=0}^{J-1} \frac{\omega_j^w}{1-\omega_0^w} \hat{w}_{t,t-j}^* - \sum_{j=2}^{J-1} \frac{\omega_j^w}{1-\omega_0^w} \left[\sum_{k=1}^{j-1} \hat{\pi}_{t-k}^w \right] \tag{34}$$

7.2 When is price stability better than wage stability?

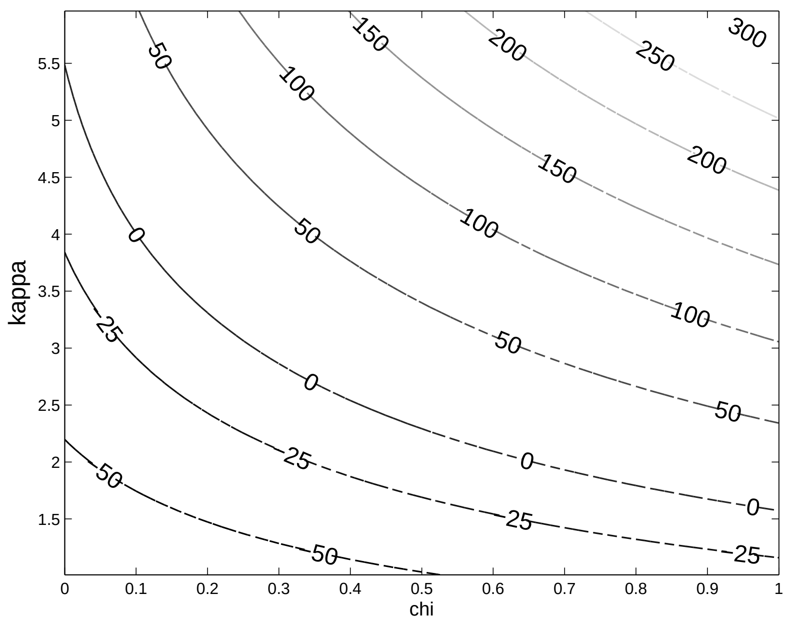

Figure 6: Contour graph: Percentage loss under price stability minus loss under wage stability in percentage terms of loss under wage stability as a function of κ and χ for $\epsilon = 7.66$. Calvo wage and price and wage setting.

The Figure shows the isolines of the welfare loss under price stability (rule 5) minus the loss under wage stability (rule 7) in percentage terms of the wage stability loss in the Calvo model. The isoline with value zero denotes the combinations of κ and χ for which price and wage stability fare equally well. Wage stability dominates for pairs to the northeast of that isoline, price stability dominates for pairs southwest. The graph shows that one needs fairly low values of χ and κ for price stability to outperform wage stability.

7.3 Is the type of shocks important for the welfare ranking?

To investigate whether the type of shock hitting the economy is important for the welfare ranking, we iteratively keep only shock in the model and draw from the remaining parameters to compute the welfare ratios. The following tables and histograms show that the results discussed above remain unchanged if only one shock is assumed to hit the economy.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	0.99	0.98	0.94
tr. Calvo	0.99	1.00	0.99	0.95
Wolman	0.98	0.99	1.00	0.97
Taylor	0.94	0.95	0.97	1.00

Table 12: Spearman rank correlation coefficient in sticky contracts model. Technology shocks only.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	0.99	0.98	0.94
tr. Calvo	0.99	1.00	0.99	0.95
Wolman	0.98	0.99	1.00	0.97
Taylor	0.94	0.95	0.97	1.00

Table 13: Spearman rank correlation coefficient in sticky contracts model. Taste shocks only.

correlation	Calvo	tr. Calvo	Wolman	Taylor
Calvo	1.00	0.99	0.98	0.94
tr. Calvo	0.99	1.00	0.99	0.94
Wolman	0.98	0.99	1.00	0.96
Taylor	0.94	0.94	0.96	1.00

Table 14: Spearman rank correlation coefficient in sticky contracts model. Monetary shocks only.

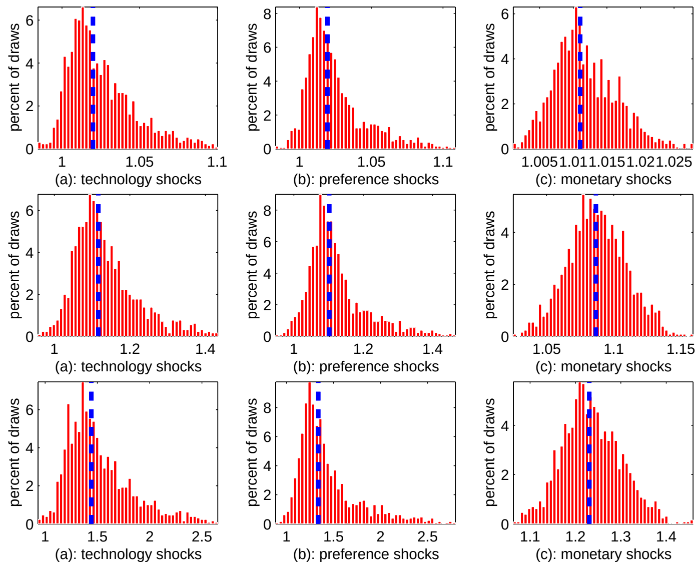

Figure 7: First row: ratio of welfare costs for Calvo contracts relative to truncated Calvo. Second row: ratio of welfare costs for Calvo contracts relative to Wolman. Third row: ratio of welfare costs for Calvo contracts relative to Taylor

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