

Using Micro Data on Prices to Improve Business Cycle Models

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Abstract

I embed the pricing model proposed by Dixon and Kara (2011a, b) (i.e. a Generalized Taylor Economy (GTE)) into a state of the art instance of New Keynesian economics (e.g. Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007)). The GTE is built to account for one of the most important features of the data: heterogeneity in price spells. I estimate the resulting model for the US using Bayesian methods. The new model matches key features of micro and macro data that would otherwise have been elusive.

Keywords: DSGE models, reset inflation, GTE, Calvo.

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1 Introduction

The Dynamic Stochastic General Equilibrium (DSGE) model developed by Christiano et al. (2005) (CEE) and later refined by Smets and Wouters (2007) (SW) has become a standard tool in modern monetary economics literature for explaining aggregate fluctuations. The model is estimated to fit US and the Euro-Area data. CEE and SW show that the model can fit the impulse-response functions of output and inflation to various shocks. Following Erceg, Henderson and Levin (2000), the model incorporates sticky prices and wages. The model also features several other frictions such as habit formation in consumption and variable capital utilisation, which are shown to be important in explaining the salient features of the aggregate series.

An important assumption of the CEE/SW framework is that wages and prices are set according to the Calvo model with indexation. A key feature of the Calvo pricing is that firms/households do not know how long their prices/wages will last. Thus, they have a probability distributions that cover different durations. As a consequence, all resetting firms/households set the same price. With indexation, prices/wages that are not reset are updated according to the past inflation rate. The Calvo model leads to a very tractable representation of price/wage inflation dynamics, making it easier to estimate the model. These features were especially important in the 1990s, when the model was first developed, since evidence in the form of micro data was particularly scarce at this time. The popularity of the Calvo model can be ascribed to its tractability, along with the empirical success of the CEE/SW framework at the macro level.

The recent surge of microevidence on prices indicates that the Calvo model with indexation is inconsistent with micro data, in at least, two dimensions¹. First, the micro-data shows that prices/wages remain unchanged

¹see for example Bils and Klenow (2004), Bunn and Ellis (2012), Dhyne, Alvarez, Bihan, Veronese, Dias, Hoffmann, Jonker, Lunnemann, Rumler and Vilmunen (2005), Klenow and Kryvtsov (2008) and Nakamura and Steinsson (2008). Klenow and Malin (2011) provide

for several months, rather than being updated according to the recent inflation rate, as suggested by the model (see Chari, Kehoe and McGrattan (2008), Cogley and Sbordone (2005), Woodford (2007) and Dixon and Kara (2010b)). SW certainly show that removing price indexation from their model does not significantly affect its performance in terms of the overall accuracy of predictions. However, as is shown by Dixon and Kara (2010b), the version of the model without indexation fails to capture the empirical observation that inflation exhibits a hump-shaped response to monetary policy shocks. Second, the Calvo pricing does not explicitly account for the heterogeneity in contract lengths observed in the data. Especially since Bils and Klenow (2004), many studies have documented that there is considerable heterogeneity in contract durations for both wages and prices. Indeed, the model's implication that all resetting firms/households set the same price/wage is unrealistic. Perhaps unsurprisingly, in a recent paper by Bils, Klenow and Malin (2012) (BKM) use micro-level price data to construct an empirical measure of reset prices and show that the SW/CEE model fails to replicate the behaviour of these statistics. BKM note that the presence of large mark-up shocks is the underlying reason for this result. In fact, the existence of implausibly large mark-up shocks leads to one of the main criticisms of the SW/CEE framework (see Chari et al. (2008)).

This paper suggests that using the recent micro-evidence on prices can improve the empirical performance of the SW/CEE model. As noted above, one conspicuous feature of the data is the heterogeneity of price spells. In this paper, I extend the SW/CEE model to account for this heterogeneity. Specifically, I reformulate the SW/CEE model by embedding the Generalised Taylor Economy (GTE) put forward by Dixon and Kara (2010a), Dixon and Kara (2010b) and Kara (2010)². The GTE is built to account for the

a summary of above-listed studies.

²To the best of my knowledge the generalisation of Taylor contracts was first suggested by Taylor (1993). More recently, Coenen, Christoffel and Levin (2007) have developed a multi-sector DSGE model with Taylor-style contracts. The authors consider contract

distribution of contract lengths. The GTE has the Calvo model as a special case. Thus, it enables consistent comparison of the two pricing rules. In the GTE there are many sectors, each with a Taylor-style contract. The Taylor process within each sector means that firms know with certainty how long their prices will last. The sectors differ in the length of contracts and their share in the economy. Firms within different sectors look at different horizons when setting their prices, in contrast to the Calvo model. In the GTE there is a distribution of reset prices. Firms focus only on the changes that occur within the duration of their particular contract. Within the Calvo framework, however, price setters assume that their prices may last for a very long time. This difference makes price setting in the GTE more myopic than that in the Calvo model. The rest of the model is the same as that outlined by SW.

Next, I use Bayesian techniques to estimate the GTE and to compare it to the SW framework with Calvo pricing. To calibrate the share of each sector (or duration) in the GTE, I use the Klenow and Kryvtsov (2008) (KK) dataset. I find that the GTE with KK-distribution (i.e. the KK-GTE) performs better than the SW model in three dimensions. First, the GTE is able to generate hump-shaped inflation in response to monetary policy shocks, without requiring the ad-hoc indexation. Second, the GTE approach reduces the need for large mark-up shocks. Third, the KK-GTE closely matches the statistics for reset price inflation. These results suggest that the KK-GTE provides a more plausible explanation of business cycle fluctuations than the SW. The two main differences are, first, that the GTE is able to account for the high-share of flexible contracts in the US economy; and, second, that price setting in the GTE is more myopic than within the

lengths up to 4 periods. Recent work by Dixon and Le Bihan (2012) combines the GTE model with a version of SW model that assumes Dixit-Stiglitz aggregator. Dixon and Le Bihan (2012) calibrate the model to French data and focus on the effects of interest rate shocks on inflation. Several recent papers suggested the generalisation of Calvo contracts. Examples include Carvalho (2006) and Nakamura and Steinsson (2010).

SW model.

The remainder of the paper is organised as follows. Section 2 presents the model. Section 3 describes the prior distribution of the parameters. Section 4 presents the results. Section 5 concludes the paper.

2 The GTE in the Smets and Wouters Model

Except for variation in price setting, the model used in this paper is the same as that described by Smets and Wouters (2007). This has become the standard model, I will keep my presentation of the model brief with a focus on the GTE model. The SW model is a general equilibrium model with monopolistic competition and capital accumulation. The model consists of households, firms and the central bank. There is a continuum of households. Households live forever and derive utility from consumption and leisure. The model assumes habit formation in consumption. Households provide labour to firms, with each household providing a unique type of labour. This assumption means that households have monopoly power over wages. Households also accumulate capital. In doing so, they face investment adjustment costs. The capital utilization is adjusted when the rental price of capital changes. Capital is then rented to firms.

The model also assumes a continuum of firms, which are owned by households. Firms employ labour and rent capital to produce differentiated goods. The labour used to produce each good is an aggregate of each household's labour. The aggregation is done according to a variant of the CES (or Dixit-Stiglitz) production function, as suggested by Kimball (1995). These goods are then combined to produce the final consumption good. Again the aggregation is done according to Kimball (1995).

Turning now to price-setting, I assume that prices are set according to the GTE, which has the Calvo model employed in SW as a special case. The unit interval of firms is divided into N sectors, indexed by $i = 1 \dots N$. Sector

N has the longest contracts in the economy, which last N periods. The share of each sector is given by α_i with $\sum_{i=1}^N \alpha_i = 1$. A Taylor process is ongoing within each sector i , such that there are i equally sized cohorts $j = 1 \dots i$ of firms. Each cohort sets a price which lasts for i periods: one cohort moves each period. The share of each cohort j within the sector i is given by $\lambda_{ij} = \frac{1}{i}$ where $\sum_{j=1}^{T_i} \lambda_{ij} = 1$.

When all the contracts have the same duration in the economy, the model reduces to a standard Taylor model. To understand why the GTE has the Calvo as a special case, first note that the Calvo model differs from the GTE mainly in that the price setters do not know how long contracts will last. In each period a randomly chosen fraction, ω , of firms/households starts a new contract. At the aggregate level, however, the Calvo process can be described in deterministic terms because the firm-level randomness washes out. As shown in Dixon and Kara (2006), the distribution of contract lengths across firms is given by $\alpha_i = \omega^2 i (1 - \omega)^{i-1} : i = 1 \dots \infty$, with mean contract length $T = 2\omega^{-1} - 1$.

2.1 The GTE

Before defining the optimal price setting rule in the GTE, it is useful to determine the optimal price that would occur if prices were perfectly flexible (p_t^*) (i.e. optimal flex price). As shown by Smets and Wouters (2007) (see also Coenen et al. (2007) and Eichenbaum and Fisher (2004)), the log-linearized version of the real optimal flex price (\bar{p}_t^*) is given by

$$\bar{p}_t^* = Amc_t \tag{1}$$

with

$$A = \frac{1}{\zeta \epsilon_p + 1} \tag{2}$$

where $\bar{p}_t^* = p_t^* - p_t$, p_t is the general price level, mc_t denotes real marginal

cost and ϵ_p is the percentage change in the elasticity of demand due to a one percent change in the relative price at the steady state. ζ is the steady state price-markup. When $\epsilon_p = 0$ and $A = 1$, we obtain the standard Dixit-Stiglitz case. A higher ϵ_p implies a lower A . Reducing A means that firms show a smaller response to the changes in marginal cost. Smets and Wouters (2007) show that mc_t in their model is given by

$$mc_t = (1 - \alpha) w_t + \alpha r_t^k - \varepsilon_t^a \quad (3)$$

Where w_t is the wage rate and r_t^k is the rental rate of capital. In the GTE, the optimal price in sector i (x_{it}) is simply the average (expected) marginal cost over the duration of the contract. The nominal price is constant over the contract length. The optimal prices will, in general, differ across sectors, since each takes an average based on a different time horizon. The average price in sector i (p_{it}) is related to the past optimal prices in that sector. The average price in the economy is simply the weighted average of all ongoing sectoral prices. Note that nominal variables such as x_{it} and p_{it} are not stationary in the model. I render them stationary by reexpressing them in terms of log-deviations from the aggregate price level. For example, \bar{x}_{it} and \bar{p}_{it} denote the logarithmic deviation of, respectively, the reset price in sector i and the price level in sector i from the aggregate price level. \bar{x}_{it} is given by

$$\bar{x}_{it} = \sum_{j=1}^{T_i} \sum_{k=j}^{T_i} \lambda_{ij+k} \pi_{t+j} + \lambda_{ij} \sum_{j=1}^{T_i} \bar{p}_t^* + \varepsilon_t^p \quad (4)$$

Where π_t is the aggregate inflation rate and ε_t^p denotes mark-up shocks. In each sector i , relative prices are related to the reset price i as follows:

$$\sum_{j=1}^{T_i} \lambda_{ij} \bar{p}_{it-j-1} = \sum_{j=1}^{T_i} \lambda_{ij} \left(\tilde{x}_{it-j-1} - \sum_{k=0}^{j-2} \pi_{t+k} \right) \quad (5)$$

In the GTE, $\lambda_{ij} = \frac{1}{T_i} = \frac{1}{i}$. These two equations can also represent the

Calvo model. To obtain the simple Calvo economy from (4), the summation is made with $T_i = \infty$ and $\lambda_{ij} = \omega(1 - \omega)^{j-1} : j = 1 \dots \infty$, where ω is the Calvo hazard rate. Based on the fact that the linearized price level in the economy is the weighted average of the ongoing prices in the economy, we obtain the following identity:

$$\sum_{i=1}^N \alpha_i \bar{p}_{it} = 0 \quad (6)$$

The aggregate real reset price is given by

$$\bar{x}_t = \sum_{i=1}^N \alpha_i \bar{x}_{it}$$

Thus reset price inflation is given by

$$\pi_t^* = \bar{x}_t - \bar{x}_{t-1} + \pi_t$$

where π_t^* is reset price inflation. The rest of the equations are exactly the same as those in Smets and Wouters (2007) and are listed in the Appendix.

2.2 Data and Prior distribution of parameters

As in BKM, I employ Bayesian techniques to estimate the models, using seven macro-economic series with bimonthly frequency³. Specifically, these seven the macro-economic series are the log difference of real GDP, real consumption, real investment, log hours worked, the log difference of the personal consumption expenditure (PCE) deflator, and the federal funds rate.

Prior distributions for the parameters are the same as those reported in BKM and Smets and Wouters (2007). These are detailed in Table 1. Let me begin by describing the assumptions concerning shock processes. The persistence of the $AR(1)$ processes is assumed to follow a beta distribution.

³I obtain these series from the dataset provided by Bils et al. (2012), which is available at <http://www.aeaweb.org/articles.php?doi=10.1257/aer.102.6.2798>. See BKM for a more detailed description of the data.

The standard errors of the shocks follow an inverse-gamma distribution. The same distribution assumption is made for the MA parameters in the ARMA process for wage and price mark-up.

The prior for the habit persistence parameter (λ) is set to 0.7, with a standard deviation of 0.1. I assume that the adjustment cost parameter (φ) follows a normal distribution. The mean of the distribution is 4 and the standard deviation 1.5. The parameter that denotes capital share in the economy is assumed to follow a normal distribution with mean 0.2 and standard deviation 0.04. The parameter governing the capital utilization elasticity (ψ) is assumed to follow a beta distribution, with mean 0.3 and standard deviation 0.05. The mean of the prior distribution of σ_l , which denotes the inverse of the labour elasticity, is set to 1.5. The Calvo probability for wages (ξ_w) is assumed to follow beta distribution with mean 0.6. The steady state price mark-up (ζ) has a prior of 1.25. The prior distribution of ϵ_p is assumed to follow a normal distribution with mean 35 and the standard deviation of 9. The trend growth rate ($\bar{\gamma}$) and the steady state values of hours worked (\bar{l}) both follow a normal distribution. The steady state inflation rate follows a gamma distribution with mean 0.625.

Turning to the parameters describing monetary policy, the coefficient on inflation (r_π) is assumed to follow a normal distribution with a mean of 1.5 and a standard error of 0.125. The coefficients on the output gap (r_y) and on the change in output gap ($r_{\Delta y}$) both follow a normal distribution with mean 0.125 and standard deviation 0.05. The lagged interest rate (ρ) is assumed to follow a normal distribution of 0.75 with a standard error of 0.1.

All of the remaining parameters have been fixed. The depreciation rate is set at 0.017. The government spending/GDP ratio is calibrated at 0.18. The curvature of the Kimball labour market aggregator (ε_w) is fixed at 10. For simplicity and without loss of generality, I set $\beta = 1$ and $\sigma_c = 1$.

These assumptions are common across the models employed in this paper. In the GTE the share of each sector is calibrated according to the Klenow

and Kryvtsov (2008) dataset. The data are derived from the US Consumer Price Index data collected by the Bureau of Labor Statistics. The period covered is 1988-2005, and the data falls into about 300 categories accounting for about 70% of the CPI. The dataset provides the average proportion of prices changes per month for each category. I interpret these statistics as Calvo reset probabilities. I then generate the distribution of durations for each category using the formula proposed by Dixon and Kara (2006). I sum all sectors using the category weights. The distribution in terms of months is plotted in Figure 1, which shows a mean contract of around 15 months. There is a long tail. However, the most common contract duration is in fact just one month. I then aggregate monthly data to a bimonthly level. For the purposes of computation, the distribution is truncated at $N = 20$, with the 20-period contracts sector absorbing all of the weights of the longer contracts. In the CEE/SW model with Calvo pricing, I set ω to $\omega = 0.25$ to ensure that the mean contract length in the two models is the same.

3 Results

I consider the performance of three models: the KK-GTE, the Calvo-GTE and the SW. The Calvo-GTE is a special case of the GTE in which the distribution of durations is exactly the same as that in the Calvo model employed by SW. The distribution of durations in the Calvo model is given by $\alpha_i = \omega^2 i (1 - \omega)^{i-1} : i = 1 \dots \infty$, with mean contract length $T = 2\omega^{-1} - 1$ (plotted in Figure 1).

The rest of this section is organised as follows. Firstly, I present the posterior estimates for each of the three models. Secondly, I compare the models with reference to the marginal likelihood, which can be interpreted as a summary measure of the overall accuracy of the predictions of a model. As noted in Kass and Raftery (1995) and SW, the statistics for marginal likelihoods can be understood as a predictive probability of the data, since

the probability of the observed data occurring, conditional upon prior beliefs, is calculated, as if the data was not available. I also compare the impulse responses from the model to those from VARs. It is also a common practice in the literature to compare the impulse responses from each model to those from VARs (see for example Woodford (2003)). The assumption is that the impulse response functions implied by a parameterized VAR model fit the data better than those implied by structural models. Finally, I will examine the extent to which the models are consistent with the data on reset inflation.

Before presenting my results, let me briefly summarise the differences between the models. The Calvo-GTE differs from the SW in that price setting in the former is less forward-looking than in the latter. This is due to the fact that firms operating with the Calvo-SW model do not know how long their contract will last. As a consequence, firms have a probability distribution over contract lengths. Since there is a positive probability of any duration's occurring, firms need to look far into the future. In the GTE, by contrast, each firm knows in which sector it belongs and, therefore, how long its contract will last. Thus they only need only consider events that take place during the duration of their respective contracts. Thus, Calvo-firms are more forward-looking than their GTE counterparts. The degree of forward-lookingness (FL) can be calculated for each model. It can be defined as the weighted mean of reset prices at future dates. In the Calvo model this is given by $FL^C = \omega^{-1}$. When $\omega = 0.25$, the Calvo reset price looks forward by on average 4 periods. In the GTEs at time t in sector i there are i different cohorts and, therefore, reset prices, such that the mean forward lookingness in sector i is $(i + 1)/2$. Hence, the mean forward-lookingness in the GTE (FL^{GTE}) is

$$FL^{GTE} = \sum_{i=1}^{\infty} \alpha_i \left(\frac{i + 1}{2} \right) \quad (7)$$

When $\omega = 0.25$, in the Calvo-GTE, firms look forward 2.5 quarters. The

KK- GTE differs from the other two models in its distribution of contract lengths. As shown in Figure 1, this model accounts for the high share of flexible contracts observed in the data. Using the above formula we see that KK-GTE firms has more or less the same degree of forward-lookingness as Calvo-GTE firms. Hence, price setting in the GTE models considered here is more myopic than the equivalent Calvo model. This is true even when the models have the same mean contract length.

3.1 Posterior estimates of the parameters

Table 1 reports the means of the posterior distributions of the parameters in three models obtained by the Metropolis-Hastings algorithm⁴.

Most of the estimates are very similar across the various models, with an important exception. The estimates for parameters describing the price mark-up shock process in the KK-GTE are very different from those in the SW and in the Calvo-GTE. The estimated parameters of the ARMA(1,1) process for the price mark-up shocks reported in Table 1 suggests that the standard deviation of mark-up shocks in the KK-GTE is much lower than that of the mark-up shocks in the SW and the Calvo-GTE. At around 0.47, the standard deviation of the price-mark-up in the KK-GTE is one-third that in the SW and is one-fifth that in the Calvo-GTE.

This difference is important and deserves some thought. Before explaining the reason for the variation, it is important to note that the models exhibit a similar degree of strategic complementarity. In each model A measures the degree of strategic complementarity of firm pricing decisions (see equation 2). If $A < 1$, then the model exhibits strategic complementarity. If $A > 1$, then firm decisions are strategic substitutes. A depends on ϵ_p and ζ . The esti-

⁴The posterior distributions reported in Table 1 have been generated by 20,000 draws, from a Metropolis Hastings sampler. The first 20% of draws are discarded. In estimating each model, a step size is chosen to ensure a rejection rate of 70%. Various statistical convergence tests show that the Markov chains have converged. An appendix that documents these tests is available upon request.

Prior Distribution				Posterior Distribution		
	Distribution	Mean	SD	Mean		
				KK-GTE	SW	Calvo-GTE
φ	Invgamma	4.00	1.50	6.28	5.89	6.60
λ	Beta	0.70	0.10	0.68	0.68	0.69
ρ	Beta	0.50	0.10	0.95	0.95	0.95
r_π	Normal	1.50	0.25	1.22	1.06	1.25
r_y	Normal	0.13	0.05	0.14	0.16	0.16
$r_{\Delta y}$	Normal	0.13	0.05	0.04	0.03	0.04
α	Normal	0.20	0.04	0.21	0.21	0.21
ξ_w	Beta	0.50	0.10	0.88	0.88	0.88
σ_l	Normal	1.50	0.50	1.22	1.27	1.22
$\bar{\pi}$	Gamma	0.62	0.10	0.47	0.46	0.48
\bar{L}	Normal	0.00	2.00	-2.71	-2.57	-2.72
$\bar{\gamma}$	Normal	0.40	0.10	0.25	0.26	0.25
ψ	Beta	0.50	0.15	0.67	0.65	0.62
ζ	Normal	1.25	0.12	1.64	1.61	1.63
ϵ_p	Normal	35.00	9.00	45.77	43.16	45.11
σ_a	Invgamma	0.10	2.00	1.25	1.24	1.24
σ_b	Invgamma	0.10	2.00	0.03	0.04	0.04
σ_g	Invgamma	0.10	2.00	0.60	0.58	0.60
σ_i	Invgamma	0.10	2.00	0.24	0.24	0.23
σ_r	Invgamma	0.10	2.00	0.05	0.04	0.05
σ_p	Invgamma	0.10	2.00	0.50	0.87	0.95
σ_w	Invgamma	0.10	2.00	0.52	0.49	0.49
ρ_a	Beta	0.60	0.16	0.95	0.94	0.95
ρ_b	Beta	0.60	0.15	0.93	0.95	0.93
ρ_g	Beta	0.50	0.20	0.96	0.96	0.96
ρ_{ga}	Normal	0.50	0.25	1.18	1.17	1.17
ρ_i	Beta	0.50	0.20	0.96	0.98	0.96
ρ_r	Beta	0.50	0.20	0.53	0.53	0.53
ρ_p	Beta	0.50	0.20	0.59	0.43	0.51
ρ_w	Beta	0.50	0.20	0.30	0.21	0.28
μ_p	Beta	0.50	0.20	0.18	0.35	0.48
μ_w	Beta	0.50	0.20	0.56	0.33	0.38

Table 1: Prior and posterior distribution of parameters and shock processes (Note: SD stands for standard deviation)

mated values of these parameters are similar across the models. They imply that $A = 0.01$, which indicates a large degree of strategic complementarity. This result -namely a similar degree of strategic complementarity across the models- is especially important in the light of the claim made by BKM that the large degree of strategic complementarity in the SW is the reason why the model estimates large mark-up shocks. The presence of strong strategic complementarities in the model means that firms do not show significant responses to changes in marginal cost. Thus, prices and in turn output, in the economy adjust sluggishly. A high degree of persistence in prices is at odds with recent data on prices. Thus, to reduce the persistence of inflation and thereby to enable the SW model to generate a realistic degree of inflation, the model has a large and transitory markup shocks.

BKM's reasoning suggests that, given a degree of strategic complementarity, the magnitude of mark-up shocks increases with greater persistence of inflation. A comparison of the SW model and Calvo-GTE models confirms this suggestion. As shown by Dixon and Kara (2010a), the less forward-looking Calvo-GTE generates more persistence than the corresponding Calvo model, although the difference is small. As a consequence, an increased degree of persistence in the Calvo-GTE explains why mark-up shocks are larger in the SW model.

I now return to the reason why the mark-up shocks are lower in the KK-GTE than in the other models. Recall that compared to the Calvo-GTE, the KK-GTE has a higher share of flexible contracts. A higher share of flexible contracts in the KK-GTE means that the model generates less persistence than the Calvo-GTE, reducing the need for large markup shocks.

3.2 Model comparison

The goodness-of-fit of each models to data is evaluated using statistics for marginal likelihood and by comparing the discrepancies between impulse response functions in these models and the VAR framework. To compare

the models in terms of marginal likelihoods, I use the modified harmonic mean estimator suggested by Geweke (1990). This estimator is a numerical approximation of the marginal likelihood function based on the output of the Metropolis-Hastings algorithm. First I compare the models in terms of marginal likelihood. Table 2 presents the log-marginal likelihood for the models.

	SW	Calvo-GTE	KK-GTE
Log Marginal Likelihood	-709.40	-706.98	-708.14

Table 2: the Log-marginal Likelihood for Different Models

A comparison based on marginal likelihoods suggests that the GTE models perform better than the SW. This result indicates that the data favours models with backward-looking element in price setting. The fact that the Calvo-GTE performs the best and that the only difference between the Calvo-GTE and the SW is that price-setting in the first model is more myopic than in the latter reinforces this conclusion.

The conclusion that the GTE models perform empirically better than the SW also holds when the impulse response functions for each of these models are compared with those obtained from VARs. The particular comparison also helps to explain why the GTE models performs better in terms of marginal likelihood. Figures 2 and 3 show the estimated impulse responses of output, inflation, the interest rate, hours worked to technology shocks and to monetary policy shocks for each of the three models. The impulse responses for technology shocks are reported in Figure 2 and those for monetary policy are reported in Figure 3. Let me first focus on the effects of monetary policy shocks. The only important difference in responses is that in the GTEs inflation displays a hump-shaped response to monetary policy shocks, which is in line with empirical impulse responses (see e.g. CEE). Inflation in the

KK-GTE peaks at the 4th period. In the Calvo-GTE, it peaks later, at the 5th period. By contrast, the SW model cannot generate a hump-shaped response, unless one introduces ad-hoc indexation to the model. The maximum effect of the shock is on impact. As explained by Dixon and Kara (2010b), the GTE models are able to generate a hump shaped response to monetary policy shocks due to the fact that they are less forward-looking than the SW model. The smaller degree of forward-lookingness means that, the maximum effect of monetary policy shocks is not on impact, leading to is a hump-shaped response.

Turning to the effects of positive technological shocks, the figure shows that the economy experiences a boom. Inflation falls and gradually converges with the initial steady state. Importantly, inflation in the Calvo-GTE responds with greater persistence than in the other models. This seems to be the reason why the Calvo-GTE performs the best in terms of likelihood. It is worth pointing out that, in line with much of the empirical evidence (see for example Gali (1999)), in all three models technological improvement leads to a decline in hours.

3.3 Addressing the criticism by BKM

In a recent paper, BKM found that the SW model cannot explain the statistics for reset inflation. Here, I address this criticism. Columns (1) and (2) of Table 3 summarise the findings of BKM⁵⁶. Column (1) of Table 3 re-

⁵Column (1) is based on data from the PCE deflator, which is used to estimate the models. BKM assess the models using data based on the CPI, even though they use the PCE deflator to estimate the model. The statistics for the SW reported in Column (2) are slightly different from those reported in BKM. The variation arises due to the differences in our calibrations. I assume that the Calvo hazard rate for price is 0.25 which is the value suggested by the KK dataset, whereas BKM assume a value of 0.31. This difference arises due to the fact that BKM use the updated version of the KK-dataset. I fixed the following parameters: $\beta = \sigma_c = 1$. BKM estimate these parameters. The estimated values of these parameters are not very different from the values I fixed here.

⁶Statistics for all models are means across 100 simulations of 125 periods.

ports summary statistics for BKM’s empirical measure of reset inflation and aggregate inflation, while Column (2) of Table 3 displays the corresponding statistics for the SW model. The data suggest that reset inflation is not persistent. Serial correlation, which is measured by first-order autocorrelation, is almost zero. Aggregate inflation is more persistent than reset inflation, with a serial correlation of around 0.13. The table further indicates that aggregate inflation is less volatile than reset inflation. The standard deviation of reset inflation is around 0.66%, whereas the standard deviation of aggregate inflation is 0.33%.

The SW model can closely match the statistics on aggregate inflation. The serial correlation of aggregate inflation in the SW model is 0.17. At around 0.33%, the standard deviation of aggregate inflation is in-line with the data. However, the model fails to match the statistics for reset inflation. As noted by BKM, reset inflation in the model is more persistent and more volatile than what the data suggests. In the SW model the serial correlation of reset inflation is -0.42. The standard deviation of reset inflation in the model is twice that indicated by the data. BKM suggest that the failure of the model to match the statistics for reset inflation is due to the presence of large mark-up shocks, which must hit reset price inflation strongly to reduce the persistence of aggregate inflation induced by the presence of strong strategic complementarity.

	(1) Data	(2) SW	(3) Calvo-GTE	(4) KK-GTE
(1) Standard deviation of π^*	0.66%	1.55%	1.47%	0.87%
(2) Serial correlation of π^*	0.06	-0.42	-0.21	-0.02
(3) Standard deviation of π	0.33%	0.34%	0.33%	0.34%
(4) Serial correlation of π	0.13	0.17	0.21	0.19

Table 3: Summary Statistics for bi-monthly Reset and Aggregate Price Inflation for Data and Models

Next I consider the performance of the Calvo-GTE. The statistics for the Calvo-GTE are reported in Column (3) of Table 3. The Calvo-GTE fits the data for aggregate inflation as closely as the SW model. As noted above, however, this comes at the cost of larger mark-ups. In the model the serial correlation of aggregate inflation is around 0.2, while the standard deviation is 0.33%. These are not far from those indicated by the empirical data. Perhaps surprisingly, the table suggests that the Calvo-GTE fits the data on reset inflation better than the SW. Given the larger mark-up shocks in the former, one would expect a greater degree of negative autocorrelation in the Calvo-GTE model than in the SW model. However, this is not the case. At -0.21, the persistence of reset inflation in the Calvo-GTE is lower than that in the SW model and, therefore, closer to that displayed by the data. Again, less forward looking price setting in the Calvo-GTE is the reason for this result. To understand how myopia in price setting helps the Calvo-GTE to perform better than the SW, I consider the effects of a positive mark-up at time t . At time t when the mark-up shock hits the economy, inflation jumps in both the Calvo-GTE and the SW. However, the increase is greater in the SW than in the Calvo-GTE. This is due to the fact that when setting their prices SW firms take a longer perspective than Calvo-GTE firms. The smaller increase in inflation in the Calvo-GTE model means that reducing the persistence of inflation in the model does not require as great a degree of negative reset inflation as the SW model. Relatedly, reset inflation is less volatile in the Calvo-GTE than in the SW.

Finally, I consider the performance of the KK-GTE. The statistics for this model are reported in Column (4) of Table 3. The model does a better job than both the Calvo-GTE and the SW in accounting for the observed persistence and volatility of both reset inflation and aggregate inflation. The KK-GTE model fits the data for aggregate inflation as closely as the SW, while at the same time closely match the data on the persistence of reset inflation. In the KK-GTE it is -0.02%, while it is 0.06% in the data. The

standard deviation of reset inflation in the KK-GTE is similar to that in the data: it is 0.88%, while it is 0.66% in the data. Given the above findings, the success of the KK-GTE in tracking the data for both of the series is not surprising. The magnitude of mark-up shocks in the KK-GTE is much smaller than that in the other models considered here. Furthermore, price setting is less forward-looking in the KK-GTE than in the SW.

4 Conclusions

I have introduced heterogeneity of contracts lengths to the CEE-Smets and Wouters framework. To achieve this I put the GTE model into the CEE-Smets and Wouters framework. The GTE framework consists of many sectors, each with a Taylor style contract. The GTE is general enough that it can be used to model any distribution of contracts, including the distribution of contracts in the Calvo model. I have calibrated the share of each duration in the new model according to the evidence provided by Klenow and Kryvtsov (2008). I have estimated the new model (i.e. KK-GTE) using US data. I have shown that introducing the heterogeneity of contract length to the CEE-Smets and Wouters framework improves the fit of the model at both the macro and micro level.

The use of the KK-GTE model helps to overcome three important criticisms directed towards New Keynesian models. First, the model generates a hump shaped inflation response to interest rate shocks, without requiring the ad-hoc indexation. Second, I show that the new model tracks the empirical data on reset inflation very well, while also being consistent with data on aggregate inflation. Finally and importantly, I show that the KK-GTE approach reduces the need for large mark-up shocks. The standard deviation of mark-up shocks in the KK-GTE is only one-third of that in the Smets and Wouters model.

These findings suggest that incorporating recent microevidence on prices

into existing models can significantly improve the performance of these models and help to address the criticisms directed at them. In this paper, following CEE and SW, I assume that wages are set according to the Calvo scheme. The findings summarised above suggest that accounting for heterogeneity in wage contracts may help to address another criticism by CKM (2007) regarding an implausibly large variance of wage mark-up shocks. Unfortunately, however, micro-evidence on wages is scarce. Thus, this calls for more research to determine the shape of the distributions of wage durations. Finally, reset price inflation may be a useful concept in the formulation of monetary policy. I leave this issue as a matter of future research.

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5 Appendix: The Smets and Wouters (2007)

Model

Here I list the log-linearised equations of the Smets and Wouters (2007). The consumption Euler equation with habit formation is given

$$c_t = c_1 c_{t-1} + (1 - c_1) E_t c_{t+1} + c_2 (l_t - E_t l_{t+1}) - c_3 (r_t - E_t \pi_{t+1} + \varepsilon_t^b) \quad (8)$$

with $c_1 = \frac{\lambda/\gamma}{1+\lambda/\gamma}$, $c_2 = \frac{(\sigma_c-1)(WL/C)}{\sigma_c(1+\lambda/\gamma)}$, $c_3 = \frac{1-\lambda/\gamma}{(1+\lambda/\gamma)\sigma_c}$. λ is the habit persistence parameter and γ is the deterministic trend, c_t is consumption, r_t is the interest rate, π_t is the inflation rate, l_t is labour and ε_t^b is the exogenous risk premium process, which is assumed to follow an AR(1) process. The following equation gives the investment Euler equation

$$i_t = i_1 i_{t-1} + \frac{\beta}{1+\beta} E_t i_{t+1} + \frac{1}{(1+\beta)\varphi} q_t + \varepsilon_t^i \quad (9)$$

where $i_1 = \frac{1}{1+\beta\gamma^{1-\sigma_c}}$, $i_2 = \frac{i_1}{(\gamma^2\varphi)}$, β is the discount factor, φ is the elasticity of the capital adjustment cost function, i_t is investment, q_t is the current value of capital and ε_t^i is the exogenous process for the investment specific technology. The arbitrage equation is given by

$$q_t = q_1 E_t q_{t+1} + (1 - q_1) E_t r_{t+1}^k - (r_t - E_t \pi_{t+1} + \varepsilon_t^b) \quad (10)$$

where $q_1 = \beta\gamma^{-\sigma_c}(1 - \delta)$, r_{t+1}^k is the capital rental rate and δ is the depreciation rate. Capital (k_t) evolves according to the following equation:

$$k_t = k_1 k_{t-1} + (1 - k_1) i_t + k_2 \varepsilon_t^i \quad (11)$$

with $k_1 = \frac{(1-\delta)}{\gamma}$ and $k_2 = \frac{1-k_1}{i_2}$. δ is the depreciation rate. The aggregate production function is given by

$$y_t = \phi_p (\alpha k_t^s + (1 - \alpha) l_t + \varepsilon_t^a) \quad (12)$$

$$= c_y c_t + i_y i_t + z_y z_t + \varepsilon_t^g \quad (13)$$

where y_t is output, k_t^s is the capital services used in production, ε_t^a and ε_t^g represent respectively the productivity shock and the government spending shocks. Both are assumed to follow an AR(1) process. c_y and i_y are respectively the steady state consumption-output ratio and investment-output ratio. z_t denotes the degree of capital utilization. z_y is the steady state rental rate of capital (r_t^k). k_t^s is given by

$$k_t^s = k_{t-1} + z_t \quad (14)$$

with

$$z_t = \frac{1 - \psi}{\psi} r_k^t \quad (15)$$

where r_k^t is given by

$$r_t^k = -(k_t - l_t) \quad (16)$$

The wage setting equation with the Calvo model is given by

$$w_t = \frac{1}{1 + \beta\gamma^{(1-\sigma_c)}} [w_{t-1} + \pi_t + \beta\gamma^{(1-\sigma_c)} (E_t w_{t+1} + E_t \pi_{t+1}) - w_1 \mu_t^w] + \varepsilon_t^w \quad (17)$$

with $w_1 = \frac{(1 - \beta\gamma^{(1-\sigma_c)} \xi_w)(1 - \xi_w)}{\xi_w((\phi_w - 1)\varepsilon_w + 1)}$. $(1 - \xi_w)$ is the Calvo hazard rate, ε_w is the Kimball aggregator for the labour market, $(\phi_w - 1)$ is the steady state labour market mark-up and ε_t^w is the mark-up shock which is assumed to follow an ARMA(1,1) process. μ_t^w is the difference between the real wage (w_t) and the marginal rate of substitution between labour and consumption. It is given by

$$\mu_t^w = w_t - \left(\sigma_l l_t + \frac{(c_t - \lambda c_{t-1})}{1 - \lambda} \right) \quad (18)$$

Finally, the central bank is assumed to follow a generalized Taylor under

which the short term interest rate adjusted to respond to the changes in the inflation rate, in the output gap and in the growth rate output gap:

$$r_t = \rho r_{t-1} + (1 - \rho) (r_\pi \pi_t + r_y (y_t - y_t^*)) + r_{\Delta y} ((y_t - y_t^*) - (y_{t-1} - y_{t-1}^*)) + \varepsilon_t^m \quad (19)$$

where r -coefficients and ρ denote the coefficients in front of the targeting variables. ε_t^m is a monetary policy shock and follows a white noise process with zero mean and a finite variance.

The measurement equations are given by

$$\Delta GDP_t = \bar{\gamma} + y_t - y_{t-1} \quad (20)$$

$$\Delta CONS_t = \bar{\gamma} + c_t - c_{t-1} \quad (21)$$

$$\Delta INV_t = \bar{\gamma} + i_t - i_{t-1} \quad (22)$$

$$\Delta WAG_t = \bar{\gamma} + w_t - w_{t-1} \quad (23)$$

$$HOURS_t = \bar{l} + l_t \quad (24)$$

$$\Delta P_t = \bar{\pi} + \pi_t \quad (25)$$

$$FEDFUNDS_t = \bar{r} + r_t \quad (26)$$

where $\bar{\gamma} = 100(\gamma - 1)$, $\bar{\pi} = 100(\Pi_* - 1)$, $\bar{r} = 100(\beta^{-1}\gamma^{\sigma_c}\Pi_* - 1)$ and $\bar{l} = 0$.

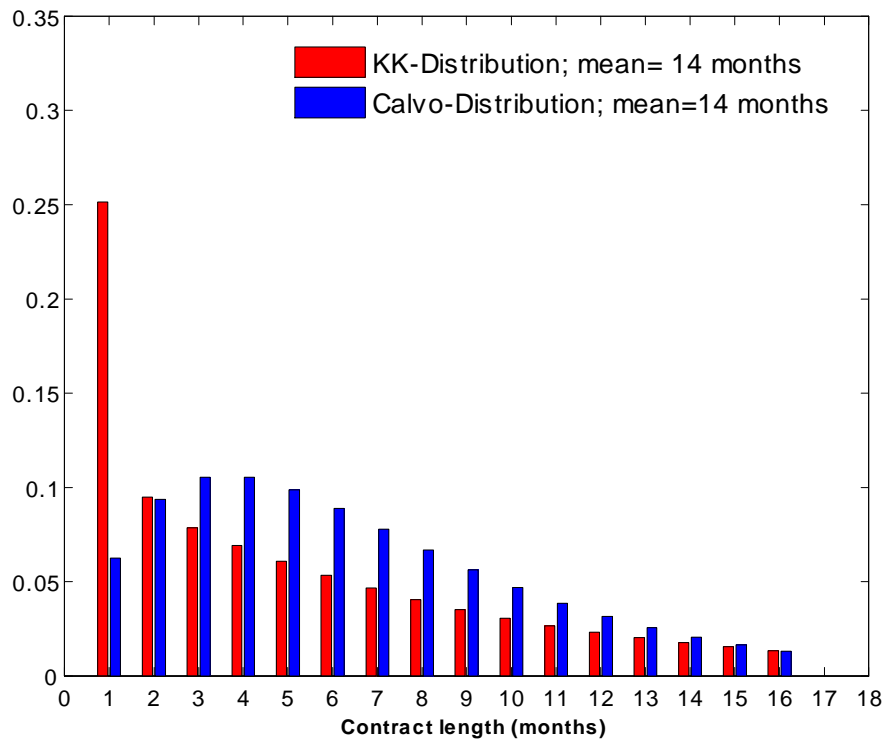


Figure 1: KK-distribution vs Calvo-distribution: the distribution of completed contract lengths (in months)

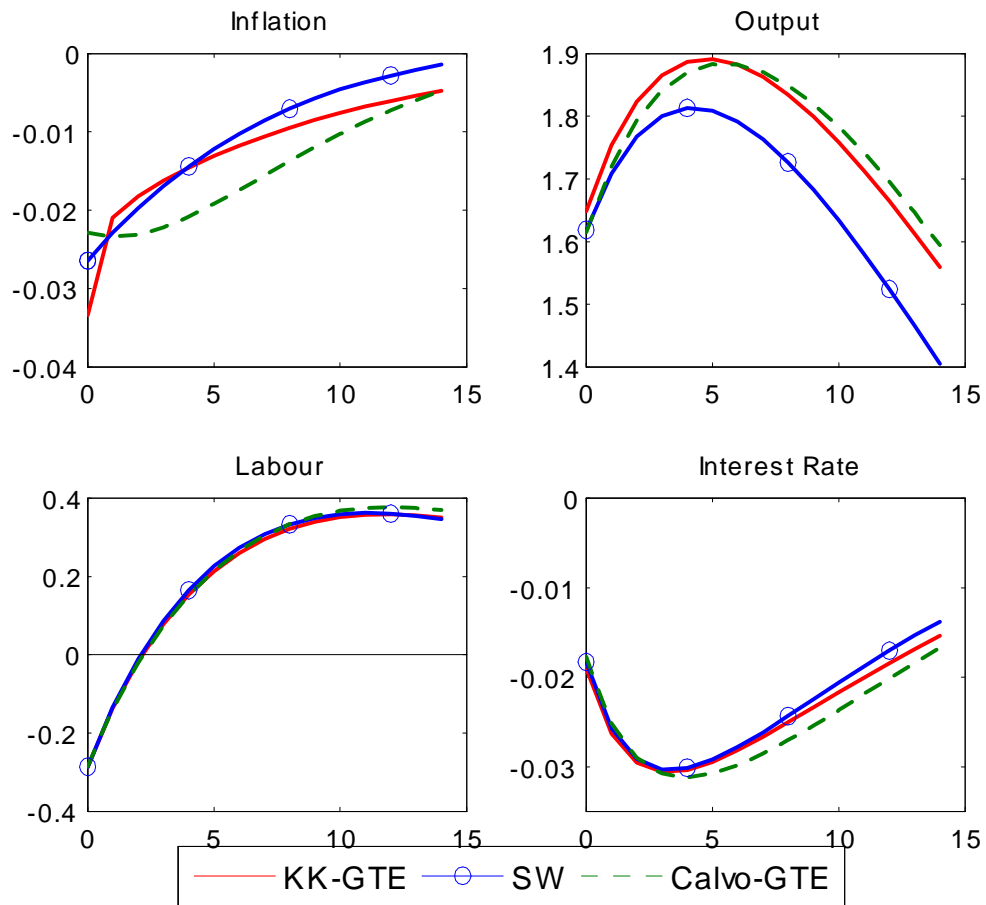


Figure 2: The impulse response functions from the model to productivity shocks

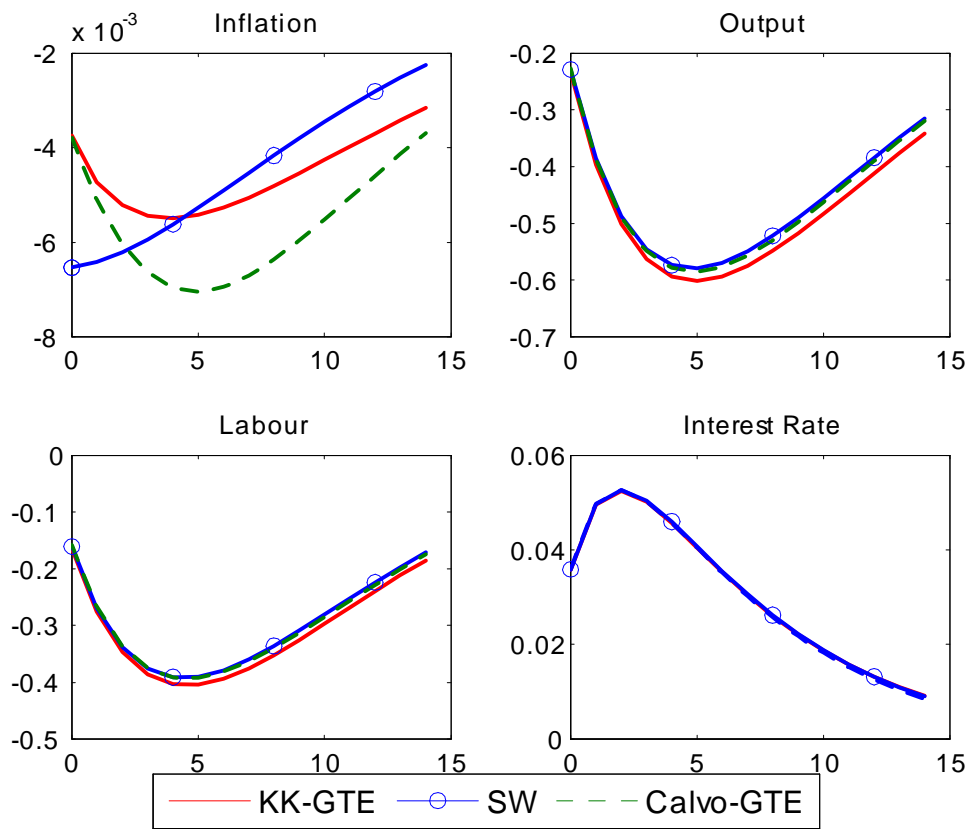


Figure 3: The impulse response functions from the model to monetary policy shocks