

1 The Reset Inflation Puzzle and the
2 Heterogeneity in Price Stickiness[☆]

3 Engin Kara*

4 *Ozyegin University*

5 **Abstract**

6 New Keynesian models have been criticised on the grounds that they
7 require implausibly large price shocks to explain inflation. Bills, Klenow, and
8 Malin (2012) show that, while these shocks are needed to reduce the excessive
9 inflation persistence generated by the models, they give rise to unrealistically
10 volatile reset price inflation. This paper shows that introducing heterogeneity
11 in price stickiness in the models overcomes these criticisms directed at them.
12 The incorporation of heterogeneity in price stickiness reduces the need for
13 large price shocks. With smaller price shocks, the new model comes close to
14 matching the data on reset inflation.

15 *Keywords:* DSGE models, selection effect, reset inflation, Calvo, GTE

16 *JEL Classification:* E10, E30

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*Department of Economics, Ozyegin University, Nisanteppe Mah. Orman Sok. 34794 Cekmekoy, Istanbul, Turkey. *E-mail address:* engin.kara@ozyegin.edu.tr

17 **1. Introduction**

18 The New Keynesian Dynamic Stochastic General Equilibrium model de-
19 veloped by Smets and Wouters (2003, 2007), which is based on the model
20 proposed by Christiano, Eichenbaum, and Evans (2005), has become a stan-
21 dard tool for monetary policy analysis. The model features several frictions
22 such as sticky prices, sticky wages, habit formation in consumption, variable
23 capital utilisation and strategic complementarities in price setting. Smets
24 and Wouters (2007) (hereafter SW) show that such a richly-specified micro-
25 founded model fits the macroeconomic data such as GDP and inflation almost
26 as well as large Bayesian VARs. Reflecting Smets and Wouters’s success, an
27 increasing number of central banks and other policy institutions have started
28 to use the model for macroeconomic forecasting and policy analysis.

29 However, recent papers by Bilts, Klenow, and Malin (2012) (hereafter
30 BKM) and Chari, Kehoe, and McGrattan (2009) (hereafter CKM) have crit-
31 icised the SW model on the basis that the model can explain the behaviour
32 of inflation only when assuming implausibly large exogenous price mark-up
33 shocks. CKM note that this is a concern since these shocks are difficult to
34 interpret. BKM show that these shocks make reset price inflation too volatile
35 relative to the data. The reset price is the price chosen by firms that can
36 change their price in the current period. It is different from the aggregate
37 price level since the aggregate price level includes the prices of firms that do
38 not change their prices in the current period. Reset price inflation is the rate
39 of change of all reset prices. BKM’s finding suggests that the model might
40 not be consistent with firm-level pricing decisions. This suggestion is partic-
41 ularly important in the light of the findings of Levin, Lopez-Salido, Nelson,

42 and Yun (2008), who establish that policy recommendations that arise from
43 New Keynesian models are sensitive to the microeconomic structure of the
44 model even when the models explain the macroeconomic data equally well.

45 BKM show that two features of the model that are commonly used to
46 generate greater monetary non-neutrality are the reasons for the failure of the
47 model. These features are price stickiness modelled using Calvo pricing and
48 strategic complementarities in price setting, which take the form of kinked
49 demand, as in Kimball (1995). Without price mark-up shocks, the model
50 with these features generates too much persistence in inflation. To match
51 the lower degree of inflation persistence in the data, the model assumes large
52 and transitory price markup shocks. These shocks succeed in cutting the
53 persistence in inflation but at the cost of creating variability in reset price
54 inflation that is far above that seen in the data.

55 Strategic complementarities in price setting, as in Kimball (1995), mute
56 the response of reset prices, since firms face an elasticity of demand that
57 is increasing in their products' relative prices and, therefore, are reluctant
58 to pass increases in marginal costs into their prices. Inflation in the model
59 responds even more sluggishly than reset price inflation because each period
60 only a fraction of firms are allowed to change prices. Moreover, in the model,
61 the firms that adjust prices are chosen randomly, implying that in the model
62 there is no "selection effect" as to which firms change their price. This means
63 that a firm whose price is close to the desired price is as likely to change price
64 as a firm whose price is far away from the desired price. This feature of the
65 model further slows the response of prices to changes in reset prices.

66 This paper takes up the challenge put forward by BKM. To achieve this, I

67 add heterogeneity in price stickiness to the model to make it consistent with
68 an implication of the micro evidence on prices (see Klenow and Malin (2011)
69 for a survey). Following Carvalho (2006), the heterogeneity in price stickiness
70 is modelled according to the Multiple Calvo (MC) model in which there are
71 many sectors, each with a different Calvo style contract. In the MC, firms
72 are divided into sectors according to the probability of adjusting their prices.
73 When all hazard rates in each sector are equal, the model gives the standard
74 Calvo model with a single economy-wide hazard rate. For the purpose of
75 this paper, the MC is an ideal model since it enables a clean comparison of
76 the SW model with and without heterogeneity in price stickiness. I replace
77 Calvo pricing in the SW model with the MC assumption, in which the share
78 of each product sector is calibrated according to micro evidence; estimate
79 the resulting SW-MC model with Bayesian techniques using US data; and,
80 finally, compare its empirical performance to the SW framework with Calvo
81 pricing.

82 The findings reported in the paper suggest that adding heterogeneity in
83 price stickiness to the SW model helps to overcome the two criticisms of the
84 model. While the SW-MC model fits the macroeconomic data as well as
85 the SW model, the variance of price mark-up shocks implied by the SW-MC
86 is much smaller than that implied by the SW model. The SW-MC matches
87 both the low degree of persistence in actual inflation and the low variability of
88 reset price inflation relative to actual inflation. Importantly, this is true even
89 though both models exhibit a similar degree of strategic complementarity in
90 price setting.

91 These results can be understood in terms of the selection effect. Carvalho

92 and Schwartzman (2014) analytically show that heterogeneity in price stick-
93 iness is associated with a smaller selection effect. A smaller selection effect
94 means that fewer firms are chosen from sectors with lower hazard rates. This
95 implies that MC firms that change their prices in a given period are dispro-
96 portionately drawn from sectors with higher hazard rates. As a consequence,
97 the price adjustment process is mainly driven by sectors with higher hazard
98 rates. Since, with lower price stickiness, the average price levels in these sec-
99 tors change more in response to temporary shocks, inflation in the SW-MC
100 varies more than in the SW. This increased volatility of inflation reduces the
101 need for highly volatile reset price inflation and, in turn, large price mark-
102 up shocks in order for the model to match the volatility of actual inflation.
103 My findings support the conclusion reached by Carvalho and Schwartzman
104 (2014) that it is the degree of the selection effect that drives the properties
105 of time-dependent models.¹

106 The remainder of the paper is organised as follows. Section 2 presents the
107 model. Section 3 presents Bayesian estimation results. Section 4 compares
108 the empirical performance of the models (the SW-MC and the SW) at the
109 macro level using different measures of relative fit. Section 5 discusses in
110 detail what it is about SW-MC that explains the macroeconomic data as well
111 as the SW but with smaller price mark-up shocks. Section 6 discusses the
112 BKM critique of the New Keynesian models. Section 7 presents robustness
113 exercises and, finally, Section 8 concludes the paper.²

¹Carvalho and Schwartzman (2014) also show that their finding holds in the sticky information model of Mankiw and Reis (2002).

²The Matlab/Dynare codes used to generate the results are available in an online

114 2. Multiple Calvo (MC) in the SW Model

115 The model presented here incorporates heterogeneity in price stickiness
116 into the SW model using the MC approach. In this section, I will first
117 present the equations describing price setting in the MC and then the re-
118 maining model equations, which are identical to a special case of the SW
119 model with logarithmic consumption utility, no discounting and no indexa-
120 tion (price and wage). The first two assumptions (logarithmic consumption
121 utility and no discounting) are made for simplicity but without significant
122 loss of generality.³ Following BKM, price and wage indexations are removed
123 from the model to make it consistent with an implication of the micro data
124 that prices and wages remain fixed for several months.

125 2.1. Optimal Price Setting in the MC

126 There is a continuum of monopolistically competitive firms indexed by
127 $f \in [0, 1]$, each producing a differentiated good $Y_t(f)$. To introduce hetero-
128 geneity in the model, the unit interval of firms is divided into segments
129 corresponding to sectors and assume a Calvo-style contract within each sec-
130 tor. The sectors differ in their shares and hazard rates. There are N sectors
131 $i = 1 \dots N$ and the share of each sector is α_i . In sector i , the hazard rate is
132 given by ω_i . A firm resetting its price in sector i in period t seeks to maximise
133 its expected discounted profits over the life of the contract subject to the de-

appendix.

³Estimating the discounting parameter and the intertemporal elasticity of substitution does not change the results significantly. Perhaps this is not surprising as the estimates for these parameters are similar to the assumed values.

134 mand curve the firm faces. Using \bar{x}_{it} to denote the logarithmic deviation of
 135 the reset price in sector i (x_{it}) from the aggregate price level (p_t), I obtain
 136 the following log-linear pricing rule for the firms in sector i

$$\bar{x}_{it} = \omega_i \bar{A} \bar{m}c_t + (1 - \omega_i)(E_t \bar{x}_{it+1} + E_t \pi_{t+1}) + \varepsilon_t^p \quad (1)$$

137 where $\bar{x}_{it} = x_{it} - p_t$ is the real reset price in sector i , p_t is the general price
 138 level and π_t is inflation.⁴ $\bar{A} = 1/(\zeta \epsilon_p + 1)$ measures how responsive the firms
 139 are to the changes in real marginal cost and is determined by two parameters:
 140 ϵ_p , which is the percentage change in the elasticity of demand due to a one
 141 percent change in the relative price at the steady state and ζ , which is the
 142 steady state price-markup and is related to the fixed costs in production.
 143 $\bar{m}c_t = (1 - \alpha) w_t + \alpha r_t^k - \varepsilon_t^a$ is the real marginal cost and depends on wages
 144 (w_t), the rental rate of capital (r_t^k) and total factor productivity (ε_t^a). In each
 145 sector i relative prices are related to the reset prices in that sector as follows:

$$\bar{p}_{it} = \omega_i \bar{x}_{it} + (1 - \omega_i)(\bar{p}_{it-1} - \pi_t) \quad (2)$$

146 where $\bar{p}_{it} = p_{it} - p_t$ denotes the logarithmic deviation of the aggregate price
 147 in sector i (p_{it}) from the aggregate price level. These two equations can
 148 also represent the Calvo model. Noting that $\bar{p}_{it} = \bar{p}_{it-1} = 0$ and dropping
 149 subscript i gives the Calvo model. The nominal aggregate price level in the
 150 economy is simply the weighted average of all ongoing prices. This relation

⁴In the MC, reset prices differ across sectors since they face different hazard rates. However, due to the random nature of the Calvo contracts, all firms within the same sector set the same price and therefore subscript f has been dropped from \bar{x}_{it} .

151 implies that

$$\sum_{i=1}^N \alpha_i \bar{p}_{it} = 0 \quad (3)$$

152 The aggregate real reset price is given by

$$\bar{x}_t = \sum_{i=1}^N \alpha_i \bar{x}_{it} \quad (4)$$

153 Thus reset price inflation is given by

$$\pi_t^* = \bar{x}_t - \bar{x}_{t-1} + \pi_t \quad (5)$$

154 where π_t^* is reset price inflation. The rest of the model equations are the
155 same as those in SW and are listed in Appendix A.1.

156 **3. Data and Estimation Results**

157 As in BKM and SW, the model is estimated using Bayesian techniques.
158 I use the same dataset and marginal prior distributions as in BKM. A brief
159 description of the dataset can be found in Appendix A.2. Tables 1 and 2
160 provide a summary of the priors.

161 “Locate Tables 1 and 2 about here”

162 To calibrate the share of each sector (or product category), the Bils and
163 Klenow (2004) dataset is used. The dataset is based on U.S. Consumer
164 Price Index (CPI) microdata. The data are derived from the U.S. CPI data
165 collected by the Bureau of Labor statistics. The period covered is from
166 1995 to 1997, and the data fall into 350 categories accounting for 69% of
167 the CPI. The dataset provides the average proportion of price changes per

168 month for each category and the corresponding category weights in the CPI.
169 These numbers are interpreted as Calvo hazard rates. For computational
170 ease, those 350 product categories are aggregated into 10 sectors, each with
171 a different hazard rate (ω_i). To do so, the statistic provided by Bils and
172 Klenow for each category is rounded to one decimal place and then summed
173 across categories with the same hazard rate using the category weights. This
174 transformation results in ten different hazard rates.⁵ The resulting mean age
175 of price spells is $\kappa = \sum_{i=1}^{10} \frac{\alpha_i}{\omega_i} = 3.46$. The hazard rate (ω) is estimated in
176 the SW approach.

177 *3.1. Posterior estimates*

178 Table 1 reports the means and the standard deviations of the posterior
179 distributions of the parameters in the SW and SW-MC models obtained by
180 the Metropolis-Hastings algorithm. Table 2 presents the results for the shock
181 processes.

182 Results reported in Tables 1 and 2 suggest that the data are informative
183 about most of the parameters, for which priors and posteriors have different
184 locations, shapes and spreads. Most of the estimates are similar across the

⁵I also estimate the model using an alternative dataset provided by Klenow and Kryvtsov (2008). Doing so does not affect the conclusions of the paper. An alternative modelling approach is to identify each product category with a sector in the model. This approach requires calibrating a 350 sector MC. When the model is re-estimated with this approach, the main results of the paper are not affected. This finding is not too surprising since, reflecting the fact that many product categories have similar hazard rates, the standard deviation of durations of price rigidity in the two distributions are similar. The standard deviation of durations are around 4.

185 two models, with an important exception. The estimates for parameters
186 describing the price mark-up shock process (i.e. σ_p , ρ_p and μ_p) in the SW-
187 MC are very different from those in the SW. At around 0.33%, the implied
188 standard deviation of mark-up shocks in the SW-MC is much lower than that
189 of the mark-up shocks in the SW (0.91%).

190 The above finding is true even though the two models have almost exactly
191 the same average degree of price stickiness and exhibit a similar degree of
192 strategic complementarity of firm pricing decisions. The estimated average
193 age of price contracts (i.e. $1/\omega$) in the SW is 4 bi-months, while the cor-
194 responding mean in the SW-MC is 3.5 bi-months.⁶ \bar{A} , which measures the
195 degree of strategic complementarity of firm pricing decisions, is almost the
196 same in both models. It is 0.029 in the SW-MC, while it is 0.037 in the SW.

197 These findings bring up a natural question: why are the price mark-up
198 shocks smaller in the SW-MC? To provide an answer to this question requires
199 showing that the SW-MC explains inflation and the other observed variables
200 equally well and that the smaller price mark-up shocks are not a consequence
201 of a deterioration in the model's ability in explaining inflation and the other
202 observed variables. This is what I do in the next section.

203 4. Model Comparison

204 The empirical performance of the SW-MC relative to the SW model is
205 tested by using three measures of relative fit. The models are first compared

⁶As noted above, the hazard rates are calibrated in the SW-MC, whereas the hazard rate in the SW is estimated. I also estimate the SW model subject to the hazard rate implied by the distribution in the MC (i.e 1/3.5). My conclusions remain unchanged.

206 using Bayes Factors, and then by comparing the standard deviations of the
207 observed variables in the models and those in the data. Finally, given that
208 much of this work is motivated by the recent behaviour of inflation, the
209 behaviour of actual inflation during the sample period is compared to that
210 implied by the models.

211 The first two rows of Table 3 report the log marginal data densities for the
212 two models and the corresponding Bayes Factors by taking the SW model
213 as the reference model. For the SW-MC, the log marginal data density is
214 -712.9, while it is -713.4 for the SW. These numbers imply a Bayes factor of
215 around $e^{0.5}$, meaning that the SW-MC performs slightly better than the SW
216 model in explaining the aggregate data.

217 “Locate Table 3 about here”

218 The third through eighth rows of Table 3 report the standard deviations
219 of the observed variables in the models and those in the data. Again, as is
220 evident from Table 3, the SW-MC performs as well as the SW in accounting
221 for the standard deviations of the observed variables.

222 Turning to the behaviour of inflation, persistence in actual inflation is low,
223 due to the sample period considered in this paper (1990-2009) (see BKM and
224 references therein for a discussion of this point). The first-order autocorrela-
225 tion coefficient for actual inflation is as low as 0.13. This measure of inflation
226 persistence in both models is 0.13, that is a spot on with the empirical esti-
227 mate.

228 “Locate Figure 1 about here”

229 Finally, it is instructive to compare the impulse response function (IRF) for
230 actual inflation estimated by BKM by using an ARMA(6,6) process with
231 those for the models. Figure 1 plots the estimated cumulative IRF for actual
232 inflation to a 1% shock along with those for the models. The model IRFs are
233 generated by fitting an ARMA (6,6) process to the data simulated from the
234 models, just as BKM do on the actual data. The empirical response exhibits
235 a hump-shaped response. It builds in the first couple of periods but then
236 gradually goes back to its initial value within 15 periods. The SW model
237 IRF differs sharply from the empirical IRF in that the IRF in the SW builds
238 over time, whereas in the data it returns to its long-run value. The IRF in
239 the SW-MC is closer to the empirical pattern. Although initially the SW-MC
240 IRF is lower than that of the data, the model IRF matches the empirical IRF
241 closely.

242 **5. What Explains the Smaller Price Mark-up Shocks?**

243 This section explains what it is about the MC that fits the macroeconomic
244 data as well as the SW but with smaller price mark-up shocks. Before doing
245 this, it is useful to recap the SW case.

246 Without price mark-up shocks, the SW generates a degree of inflation
247 persistence that is significantly larger than seen in the data. The serial
248 correlation of inflation in this version of the model is as high as 0.9. Relatedly,
249 the model inflation rate is less volatile than in the data. The high degree of
250 persistence is a consequence of the model's assumptions of Calvo pricing and
251 strategic complementarities. These assumptions give rise to a flat Phillips
252 curve, meaning that changes in marginal cost have little impact on inflation

253 and, therefore, it takes time for the changes to be reflected in prices. To bring
254 inflation's persistence in line with the lower degree of persistence observed in
255 the data, the model includes a large and transient price markup shock. This
256 shock differs from the other shocks in that it is the only shock that does not
257 affect inflation through marginal cost. It affects inflation through its effect
258 on reset prices. With price mark-up shocks, the persistence of inflation is
259 0.13, the same as that for the data. To understand how transitory price-
260 mark shocks reduce the persistence in inflation, consider the effects of such
261 a shock on inflation and reset prices. When such a shock hits the economy
262 in period t , firms resetting their prices increase their prices. Soon after
263 period t , the shock is completely gone and the reset prices become too high,
264 relative to what they should be. As a result, firms resetting their price in the
265 second period reversed the initial price increase, resulting in negative reset
266 price inflation. So, a period of above-average reset price inflation is followed
267 by a period of below-average reset price inflation, thus cutting inflation's
268 persistence considerably. While this results in volatile reset price inflation,
269 due to price stickiness, inflation does not change much. Therefore, to match
270 the volatility of inflation, the required size of the price mark-up shock must
271 be large. For these reasons, as noted by BKM and SW, inflation in the model
272 is mainly explained by the price mark-up shocks.

273 To understand the reason why the required standard deviation of the price
274 mark-up shocks is lower in the SW-MC, first note that adding heterogeneity
275 in price stickiness to the model affects the price adjustment process in two
276 important ways. First, the presence of heterogeneity in price stickiness in
277 the SW-MC brings about a smaller selection effect. This is because in such

278 a model firms that change their prices in a given period are not an unbiased
279 sample of the total population of firms, as in the Calvo model. Rather, they
280 are mostly chosen from the sectors with higher hazard rates. Second, the
281 presence of the sectors with lower hazard rates in the model can significantly
282 increase the persistence of inflation, as prices in these sectors take longer to
283 adjust. As a result, the MC can generate more inflation persistence than the
284 corresponding Calvo model. This discussion suggests that the earlier part of
285 the price adjustment process is dominated by the sectors with higher hazard
286 rates, while the later part of the process is driven by the sectors with lower
287 hazard rates.

288 The first difference has important implications for the volatility of in-
289 flation and leads to more volatile inflation in the SW-MC than in the SW.
290 This is because in the SW-MC sectors with higher hazard rates, the average
291 price levels vary a lot in response to temporary shocks, as in these sectors
292 a larger proportion of firms adjust their prices in each period. Since these
293 sectors dominate the earlier part of the price adjustment process, the aggre-
294 gate price level varies more in response to temporary shocks, leading to more
295 volatile inflation in the SW-MC. As a consequence, the required size of price
296 mark-up shocks to match the volatility of inflation is smaller in the SW-MC.

297 **6. Reset Price Inflation: Addressing the BKM critique**

298 This section addresses the criticism of BKM of New Keynesian models,
299 indicating that the reset price inflation implied by the model is too volatile
300 relative to that seen in the data. As discussed earlier, the reason for the
301 implausibly volatile reset price inflation in the SW model is the presence of

302 temporary and large price mark-up shocks. My finding that the price mark-
303 up shocks are smaller in the SW-MC suggests that the SW-MC may match
304 the statistics on reset price inflation better than the SW model with Calvo
305 pricing. I now consider this suggestion.

306 Let me first describe the problem pointed out by BKM. Table 4 reports
307 summary statistics for reset inflation from the data and the models. Column
308 (1) of Table 4 shows the statistics from the data and Column (2) for the
309 SW. The reset price inflation implied by the SW model is significantly more
310 volatile than the data. The standard deviation of reset inflation in the model
311 is around 1.6%, a value that is 2.5 times larger than indicated by the data.
312 The reset price inflation in the SW model is more persistent than in the data.
313 The serial correlation of reset inflation, which is measured by its first-order
314 autocorrelation, is -0.42, whereas it is 0.06 for the data. The behaviour of
315 the model's reset price inflation is different from that of actual reset price
316 inflation also at longer horizons. To show this, BKM estimate an IRF for reset
317 price inflation by using an ARMA(6,6) process, both for the model and the
318 data. The one-year cumulative IRF for reset price in the SW is around 0.31
319 which is about half of what it is for the empirical IRF. Moreover, the model's
320 one year cumulative IRF for inflation is almost four times that for reset price
321 inflation. In the data, this ratio is only one and a half. This difference
322 suggests that, conditional on reset price inflation, the model generates too
323 much persistence relative to the data.

324 "Locate Table 4 about here"

325 I now evaluate the extent to which the SW-MC matches the statistics on
326 reset price inflation. Column (3) of Table 4 reports the statistics for the SW-

327 MC. As suggested above, reflecting the lower price mark-up shocks, the SW-
 328 MC closely match the data on reset price inflation. The standard deviation
 329 of reset price inflation is now within a striking distance of the data. It is
 330 0.77% in the SW-MC, while it is 0.66% in the data. Heterogeneity in price
 331 stickiness increases the serial correlation of reset price inflation in the model
 332 considerably, from -0.42 to -0.19. The one-year cumulative IRF for reset
 333 inflation almost matches that for the data. The one-year cumulative IRF for
 334 inflation is 0.51, while it is 0.61 in the data. Moreover, at around 2, the ratio
 335 between the one-year cumulative IRF for inflation and that for reset price
 336 inflation in the SW-MC is not far from the data's 1.5.

337 These findings bring up a natural question: given that the inflation dy-
 338 namics in both models are similar, why is reset price inflation smoother in
 339 the SW-MC? This can be easily understood by examining aggregate reset
 340 price in the SW-MC. Aggregating equation (5) across sectors and noting
 341 that $\bar{p}_{it} = \bar{p}_{it-1} + \pi_{it} - \pi_t$ gives aggregate (real) reset price

$$\bar{x}_t = \sum_{i=1}^N \frac{\alpha_i}{\omega_i} (\pi_{it} - \pi_t) + \sum_{i=1}^N \alpha_i \frac{1 - \omega_i}{\omega_i} \pi_t \quad (6)$$

342 This equation shows aggregate real reset price depends on inflation and
 343 inflation gaps (i.e. the difference between inflation in sector i and aggregate
 344 inflation). In the one sector model, the aggregate real reset price is simply
 345 a function of inflation ($\bar{x}_t = \frac{1-\omega}{\omega} \pi_t$). Given the fact that the inflation gaps
 346 in the sectors with lower hazard rates take longer to close, reset price in the
 347 SW-MC adjusts more sluggishly than in the SW model.

348 7. Robustness

349 The aim of this section is to show that the main conclusions of the paper
350 are not an artifact of the assumed distribution of price spells and hold even
351 in simple two sector models. I will also check the robustness of my results
352 to an alternative way of modelling heterogeneity in price stickiness using the
353 Generalised Taylor Economy (GTE) (see Dixon and Kara (2010)).

354 7.1. Two-sector MCs

355 Simple two-sector MCs in which the sectors have equal shares are con-
356 sidered. The assumed relative degree of price stickiness in the two sectors,
357 defined by $RS = \omega_1/\omega_2$, is varied by changing the parameters indicating the
358 degree of price stickiness in the sectors (i.e. ω_1 and ω_2) across a range of
359 values, while assuming the overall degree of price stickiness, as measured by
360 $\kappa = \frac{1}{2} \sum_{i=1}^2 1/\omega_i$, is the same as that implied by the SW model ($1/\omega$). In all
361 cases prices in sector 1 are more flexible than prices in sector 2. Assuming
362 $RS=1$ gives the SW case. Each of the resulting models is then estimated, as
363 described in Section 3.⁷

364 The results from this experiment suggest that the required standard de-
365 viations of price mark-up shocks and the standard deviation of reset price
366 inflation become smaller, as relative price stickiness increases. This is true
367 even though inflation's persistence in the two-sector economies is more or
368 less the same as that in the SW. The results further suggest that reset price

⁷In each case, the performance of the two-sector model at the macro level with that of the SW is compared using Bayes Factors. Results (not reported) suggest the two-sector models perform as well as the one-sector SW model in terms of Bayes Factors.

369 inflation becomes more persistent as relative price stickiness increases. These
370 findings are consistent with the findings obtained using the SW-MC. With an
371 increased mean preserving spread, prices in the sector with relatively flexible
372 prices become more flexible, while prices in the sector with relatively sticky
373 prices become stickier. Increased price flexibility in the sector with relatively
374 flexible prices increases the variability of the average price level in this sector
375 and, in turn, the variability of inflation. Therefore, the required size of price
376 mark-up shocks and, consequently, the standard deviation of reset price in-
377 flation becomes smaller, as relative price stickiness increases. Finally, reset
378 price inflation becomes more persistent since prices in the sticky price sector
379 become stickier, as the mean preserving spread increases. As a consequence,
380 the inflation gap in the sticky sector takes longer to close, leading to a more
381 persistent reset price. Figure A.1 in Appendix A.3 illustrates these points.

382 The above results confirm the finding that there is a tight link between
383 heterogeneity in price stickiness and the size of price mark-up shocks and that
384 allowing even a small degree of heterogeneity improves the performance of
385 the model. If the heterogeneity in price stickiness in the model is sufficiently
386 large, a simple two-sector MC can match the modest persistence in actual
387 inflation as well as the low variability of reset price inflation relative to actual
388 inflation. Micro evidence on prices does suggest that there is a significant
389 degree of heterogeneity in price stickiness.

390 *7.2. The GTE*

391 It may be useful to note that the type of price stickiness also matters for
392 the results but not as significantly as the heterogeneity in price stickiness. To
393 show this, I estimate the model by replacing the MC with the Generalised

394 Taylor Economy (GTE) (see Dixon and Kara (2010)), in which there are
395 many sectors, each with a Taylor-style contract. While the main results
396 remain unchanged, the standard deviation of price mark-up shocks is slightly
397 higher in the GTE (0.52%) than in the MC (0.33%). This is because selection
398 for older prices is stronger in the GTE than in the MC. This is true since
399 although in both models resetting firms are mostly drawn from sectors with
400 relatively more flexible prices, in the GTE, within each sector, price-changing
401 firms are always the ones whose prices have been in place for longest. As a
402 consequence, the sectoral price levels in the GTE do not change as much as
403 they do in the MC. Thus, the GTE requires larger price mark-up shocks to
404 match the volatility of inflation. These results reinforce the insight that the
405 selection effect is the driving force behind the results.

406 **8. Summary and Conclusions**

407 The Smets and Wouters (2007) model has been reformulated to account
408 for the heterogeneity in price stickiness observed in the data. Price stickiness
409 is modelled according to the Multiple Calvo (MC) approach proposed in
410 Carvalho (2006). The MC consists of many sectors, each with a Calvo-style
411 contract. The share of each sector is calibrated according to the micro-
412 evidence on prices. The resulting model is estimated using US data from
413 1990 to 2009.

414 I have first established that the new model fits the macroeconomic data
415 as well as the Smets and Wouters (2007) model and then show that account-
416 ing for the heterogeneity in price stickiness suggested by micro evidence on
417 prices helps to overcome two recent criticisms of the New Keynesian models.

418 These criticisms are, first, that the Smets and Wouters model relies on unre-
419 alistically large price mark-up shocks to explain the data on inflation; and,
420 second, that reset price inflation implied by the model is too volatile relative
421 to what we see in the data. The SW with the MC accounts for the observed
422 inflation dynamics with much smaller price mark-up shocks and comes close
423 to matching the data on reset inflation.

424 The failure of the Smets and Wouters model is a consequence of generating
425 far too much persistence in inflation. To match the persistence and volatility
426 of inflation, the model assumes large and temporary price mark-up shocks.
427 However, these shocks lead to implausibly volatile reset price inflation. The
428 reformulated Smets and Wouters model with heterogeneity in price stickiness
429 performs better since the price level changes more in response to temporary
430 shocks in this model, which reduces the need for large price mark-up shocks.
431 This is true since in the new model the sectors with more flexible prices are
432 predominant in the price adjustment process, as the resetting firms are chosen
433 disproportionately from sectors with more flexible prices. With lower price
434 stickiness, the average price levels in these sectors change more in response
435 to temporary shocks, resulting in more volatile inflation. As a result, given
436 that price mark-up shocks directly hit reset prices, smaller price mark-up
437 shocks mean that reset price inflation is less volatile in the version of the SW
438 model with heterogeneity in price stickiness than without.

439 These findings clearly show that incorporating recent micro evidence on
440 prices into existing New Keynesian models can significantly improve the per-
441 formance of these models. In this paper, following Smets and Wouters (2007),
442 wages are assumed to be set according to the Calvo scheme. Given the above

443 findings, accounting for heterogeneity in wage contracts may help to address
444 another criticism by Chari, Kehoe, and McGrattan (2009) regarding an im-
445 plausibly large variance of wage mark-up shocks. Unfortunately, however,
446 micro evidence on wages is scarce. Thus, this calls for more research to de-
447 termine the shape of the distributions of wage durations. Finally, reset price
448 inflation may be a useful concept in the formulation of monetary policy. I
449 leave this issue as a matter of future research.

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Table 1: Prior and Posterior Estimates of Structural Parameters

		Prior Distribution		Posterior Distribution			
		type	Mean	St. Dev.	SW		SW-MC
Mean	St. Dev.				Mean	St. Dev.	Mean
φ	Normal	4.00	1.50	6.29	1.16	6.53	0.01
h	Beta	0.70	0.10	0.68	0.04	0.69	0.04
ξ_w	Beta	0.50	0.10	0.87	0.03	0.88	0.03
σ_l	Normal	2.00	0.75	1.24	0.35	1.27	0.35
ω	Beta	0.50	0.10	0.25	0.04	—	—
ψ	Beta	0.50	0.15	0.64	0.12	0.64	0.13
Φ	Normal	1.25	0.12	1.63	0.10	1.70	0.09
r_π	Normal	1.50	0.25	1.22	0.16	1.24	0.18
ρ	Beta	0.75	0.10	0.95	0.01	0.95	0.01
r_y	Normal	0.12	0.05	0.16	0.03	0.15	0.04
$r_{\Delta y}$	Normal	0.12	0.05	0.04	0.01	0.04	0.01
α	Normal	0.30	0.05	0.21	0.02	0.21	0.02
$\bar{\Pi}$	Gamma	0.62	0.10	0.45	0.04	0.44	0.03
\bar{L}	Normal	0.00	2.00	-2.57	0.82	-2.53	0.90
ϵ_p	Normal	35.0	9.00	43.04	8.06	47.31	7.01
$\bar{\gamma}$	Normal	0.40	0.10	0.26	0.02	0.26	0.03

Notes: SW-MC denotes the baseline model, i.e., Smets and Wouters' (2007) model with heterogeneity in price stickiness. SW refers to Smets and Wouters' original formulation. In the SW-MC, the share of each sector is calibrated according the Bils and Klenow (2004) dataset, while the Calvo hazard rate (ω) in the SW model is estimated. The columns 'Mean' and 'St. Dev.' list the means and the standard deviations of the prior and posterior distributions.

Table 2: Prior and Posterior Estimates of Shock Processes

		Prior Distribution		Posterior Distribution			
				SW		SW-MC	
type		Mean	st. dev.	Mean	st. dev.	Mean	st. dev.
σ_a	Invgamma	0.10	2.00	1.24	0.10	1.2	0.09
σ_b	Invgamma	0.10	2.00	0.04	0.01	0.04	0.01
σ_g	Invgamma	0.10	2.00	0.6	0.05	0.61	0.04
σ_I	Invgamma	0.10	2.00	0.24	0.05	0.23	0.04
σ_r	Invgamma	0.10	2.00	0.05	0.00	0.05	0.00
σ_p	Invgamma	0.10	2.00	0.91	0.24	0.29	0.03
σ_w	Invgamma	0.10	2.00	0.48	0.04	0.49	0.05
ρ_a	Beta	0.50	0.20	0.93	0.01	0.94	0.01
ρ_b	Beta	0.50	0.20	0.93	0.02	0.93	0.03
ρ_g	Beta	0.50	0.20	0.96	0.01	0.96	0.01
ρ_I	Beta	0.50	0.20	0.97	0.02	0.97	0.02
ρ_r	Beta	0.50	0.20	0.53	0.06	0.53	0.06
ρ_p	Beta	0.50	0.20	0.43	0.14	0.62	0.06
ρ_w	Beta	0.50	0.20	0.29	0.16	0.30	0.16
μ_p	Beta	0.50	0.20	0.35	0.16	0.21	0.10
μ_w	Beta	0.50	0.20	0.37	0.13	0.38	0.12
ρ_{ga}	Beta	0.50	0.20	1.17	0.06	1.21	0.06

Notes: See the description notes in the previous table.

Table 3: Summary Statistics for the models

Statistics	Data	SW	SW-MC
(1) Log Marginal Data Density	–	-713.35	-712.89
(2) Bayes Factor versus SW	–	1.00	$e^{0.46}$
<i>Standard Deviations</i>			
(3) Output Growth	1.85	1.97	1.98
(4) Consumption Growth	0.45	0.71	0.71
(5) Price Inflation	0.33	0.33	0.35
(5) Wage Inflation	0.80	0.91	0.90
(6) Investment	1.88	3.38	3.35
(7) Interest Rate	0.34	0.30	0.30
(8) Labour	3.60	3.95	3.90

Notes: Row (1) reports the Marginal density for each model and Row (2) the corresponding Bayes Factors by taking the SW as a reference model. Rows (3)-(8) report the standard deviations from the model and from the data. In Rows (3)-(8), statistics are averages across 100 model simulations, each of 119 periods. Increasing the number of simulations to 500 or 1000 draws does not change the results.

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Table 4: Summary Statistics for Inflation and Reset Price Inflation

Statistics	Data	SW	SW-MC
Standard Deviation of π	0.33%	0.35%	0.35%
Serial Correlation of π	0.13	0.13	0.13
Standard deviation of π^*	0.66%	1.61%	0.77%
Serial Correlation of π^*	0.06	-0.42	-0.19
$\frac{1 - \text{year cumulative } \pi}{1 - \text{year cumulative } \pi^*}$	1.5	3.8	2.2

Notes: In Rows, (1)-(4), statistics are averages across 100 model simulations, each of 119 periods. Increasing the number of simulations to 500 or 1000 draws does not change the results. The data statistics are reported in Column (1), while the models' statistics are reported in Columns (2) and (3).

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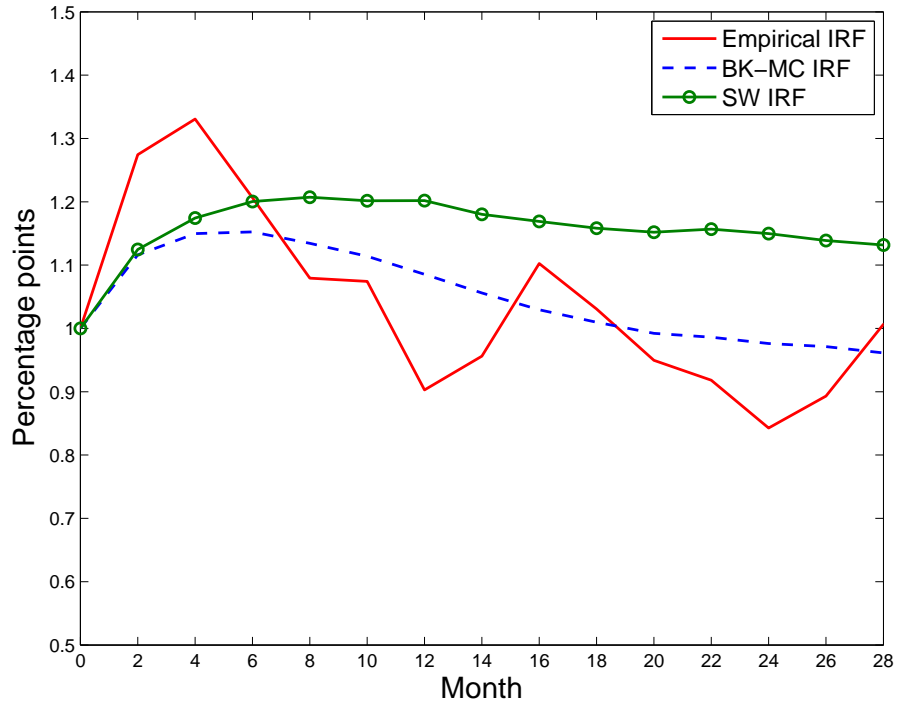


Figure 1: Impulse Response Functions (IRF) of Reset Price Inflation: Empirical Response vs Model Responses

Notes: Plotted are accumulated responses to ARMA(6,6) for reset price inflation. The empirical IRF is estimated by BKM and is based on CPI-RDB data for all items.