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HETEROGENEITY IN WAGE SETTING BEHAVIOR IN A NEW-KEYNESIAN MODEL

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In this paper we estimate a New-Keynesian dynamic stochastic general equilibrium (NK DSGE) model with heterogeneity in price and wage setting behavior. In a recent study, Coibion and Gorodnichenko develop a DSGE model, in which firms follow four different types of price setting schemes: sticky prices, sticky information, rule-of-thumb, or flexible prices. We enrich Coibion and Gorodnichenko framework by incorporating heterogeneity in nominal wage setting behavior among households. We solve this DSGE model and estimate it using Bayesian techniques for the US economy from 1955 to 2008. The estimation results show the relevance of heterogeneity in wage setting among households. More importantly, we identify qualitative and quantitative business cycle features allowed by the heterogeneity in wage rigidity, such as the persistence in price and wage inflation, which a standard NK model with only Calvo-type wage rigidity fails to achieve. We also show that modeling wage-rigidity heterogeneity—as opposed to standard Calvo wages—amplifies the macroeconomic output fluctuations resulting from a technology shock while it mitigates the output fluctuations following a monetary tightening.

Keywords: Heterogeneity, Price, Wage and Information Stickiness, Bayesian Estimation

1. INTRODUCTION

It is well documented that DSGE models require nominal rigidities (besides real frictions) to fit the data better and to replicate the dynamics observed in stylized facts. In particular, to generate the observed persistence in output and inflation,

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nominal rigidities are necessary [Woodford (2003)]. Macroeconomists usually include nominal rigidities—which differentiate New-Keynesian (NK) models from Real Business Cycle models—through an exogenous price setting behavior of firms and wage setting behavior of households. For instance, the widely applied nominal rigidity scheme proposed by Calvo (1983) assumes that in every period only a fraction of randomly selected agents is allowed to set their prices or wages.[1] This approach, despite its convenience, is unappealing for two reasons. First, Calvo-type nominal rigidity leaves the mechanism unexplained by which a subset of firms are allowed to re-optimize their prices (or the wages for the case of households), while others are unable to do so.[2] Second, the underlying assumption of the Calvo scheme, in which agents that re-optimize their prices or wages re-optimize at the same time, is at odds with the behavior of firms and as workers observed in microdata.

Alternative approaches have been proposed in the DSGE literature to address the abovementioned two limitations of the Calvo scheme. These alternatives include, for example, the use of state-dependent pricing and modeling of the nominal frictions using information rigidities instead of price rigidities and the utilization of more general specifications, which maintain the Calvo approach but incorporate some refinements and extensions to increase modeling flexibility. To this end, for instance, Coibion and Gorodnichenko (2011) suggest that modeling an economy by assuming a uniform price setting rule across firms has non-trivial consequences related to the ability of the model to fit the data, and, more importantly, for the determination of optimal monetary policy.

Our paper is related to this latter strand of literature and its contribution is twofold. First, we complement the studies dealing with the general equilibrium implications of heterogeneity in nominal rigidities. This is achieved by allowing heterogeneity in prices akin to Coibion and Gorodnichenko (2011) and extending their specification simultaneously to the wage setting heterogeneity among households. Specifically, we develop an NK DSGE model where firms and households are divided into four types and use their monopolistic power to set prices and wages according to four different rules. The rules we consider are *Sticky prices a la Calvo*, *sticky information*, *full flexibility*, and *indexation*. We use Bayesian techniques to estimate the model for the US economy for the period of 1955–2008, when the zero-lower bound was not binding. We also estimate alternative model specifications, where nominal rigidity heterogeneity is considered only partially for prices as well as wages. The second contribution of our work is related to the use of the estimated models to investigate the macroeconomic impact of the heterogeneity in prices and wages over the business cycle—as in, for example, Aoki (2001), Carvalho (2006), and Stahlschmidt (2007).

Our key estimation results can be summarized as follows: We find that about 90% of firms follow Calvo-type price stickiness or informational stickiness when setting their prices—a quantitative result matching the findings of Coibion and Gorodnichenko (2011). As a novel finding of this paper, we show that at the household side only a total of 58% of the workers set their wages via Calvo-type

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wage stickiness or information stickiness. Therefore, the estimation results point out that wage-rigidity heterogeneity is more apparent than price heterogeneity when using an NK model in matching the aggregate data. To delineate further on the dimension of heterogeneity, we find that over 20% of the households follow a flexible wage rule, while the estimated population fraction of flexible price setters turns out to be only 5%. We also show that the model which incorporates heterogeneity in both wage and price setting behavior fits the data the best among a number of alternative models whose quantitative properties we evaluate. These findings contrast with the standard way of modeling wage determination where 100% of the households follow a Calvo sticky rule and more importantly, they cast doubts on modeling price and wage setting behavior symmetrically via standard Calvo setting. In this regard, our results show that although the assumption of all firms setting their prices according to a Calvo rule could be reasonable, extending this assumption to wage determination appears to be not appropriate when matching data.

We then conduct a business cycle analysis using the estimated model to distinguish the business cycle properties generated by wage-rigidity heterogeneity from standard NK models. We identify interesting qualitative business cycle dynamics generated by the heterogeneity in wage rigidity, such as price and wage inflation persistence following monetary contractions that are prevalent characteristics of the business cycle data. Standard models with only Calvo-type wage rigidity fail to match such business cycle properties. Moreover, the impulse responses reveal that allowing heterogeneity in wage rigidity amplifies the macroeconomic output fluctuations resulting from a technology shock, whereas it mitigates the output fluctuations following a monetary tightening. As another key result, we also show that models which do not incorporate any wage rigidity generate implausible fluctuations of macroeconomic variables, such as for wage inflation.

Based on our findings, a key policy-relevant conclusion from the analysis is that the heterogeneity in wage staggeredness proves to be an important channel through which nominal rigidities could determine the level of monetary policy effectiveness. In this respect, our paper contributes to the growing literature aimed to understand the relevance of wage determination for the macroeconomy. Two important papers in this literature are Galí (2013) and Galí and Monacelli (2014). While Galí (2013) shows that in the context of a closed economy model, macroeconomic consequences of wage rigidities depend on the type of the monetary policy rule, Galí and Monacelli (2014) study the gains from wage flexibility for the case of an open economy and show that an increase in wage flexibility could reduce welfare—especially in economies under an exchange rate peg. We contribute to this important policy debate by emphasizing that it is not only the overall level of labor market flexibility but also its sectoral composition what matters for the macroeconomic policymaking.

The remainder of this paper is divided into five sections. Section 2 provides a summary of empirical findings regarding heterogeneity in price and wage setting behavior. Section 3 summarizes some findings about the relevance of wage

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rigidity for business cycles. In Section 4, the model specification, its log-linear form, and equilibrium conditions are sketched. Sections 5 and 6 discuss the estimation methodology and present quantitative results, respectively, while in Section 7, concluding remarks and suggestions for further research are presented.

2. EVIDENCE OF HETEROGENEITY IN PRICE AND WAGE SETTING

Extensive empirical literature shows that the price setting behavior is not homogeneous across firms and shows considerable variability. This variability depends on factors like the firm size, economies of scope, or the existence of explicit or implicit contracts which impede even minor adjustments in prices.

Similarly, firms can be reluctant to change prices guided by the notion that consumers could wrongly relate a reduction in price with a reduction in the quality of the products, deterring in this way downward correction in prices. In addition, competition stances or failures in coordination among firms could make a firm not willing to change the price of its products for fear that competitors will not do the same. Finally, different pricing behavior could be a consequence of the traditionally studied implication of high costs (menu costs) for changing prices, which are different among firms [Hoeberichts and Stokman (2006)].[3,4]

One study that is particularly relevant for this paper is Coibion and Gorodnichenko (2011), where the authors solve and estimate a traditional NK DSGE model with flexible wages but heterogeneity in the price setting behavior among firms. In particular, Coibion and Gorodnichenko (2011) consider that the economy is composed of four sectors whose only difference is the constraint (or lack of it) faced when setting prices. The four sectors considered are firms that use traditional sticky prices a la Calvo, firms that face sticky information, those that adjust their prices every period according to the last period's inflation, and firms that have flexible prices. Coibion and Gorodnichenko (2011) find that this kind of heterogeneity in prices improves the data fit performance of the model (casting doubts on specifications that only include one type of rigidity or none at all). Also, the authors find that the non-consideration of the heterogeneity can hinder the task of the monetary authority and complicate the achievement of its stabilization objectives.

In contrast with a large body of literature dealing with heterogeneity in the rigidity of prices among firms, there are relatively fewer papers that empirically investigate heterogeneity in wage setting behavior. The scarcity of research on this topic was due to a great extent to the lack of appropriate data. Recently, high-frequency wage data become increasingly available—leading to a new strand of research to gain momentum. For example, in the case of France, using survey data from 1998 to 2005, Bihan et al. (2012) find evidence of heterogeneity in the frequency of wage adjustments across sectors, occupations, and firm size. The authors also show a seasonal pattern in wage changes, which are more likely to occur in the first quarter. Besides the usual downward rigidity, the paper also finds a non-flat hazard function for wages having a peak in the fourth quarter.[5]

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In a similar vein, using monthly administrative data from Luxemburg from 2001 to 2006, Lünnemann and Wintr (2009) find high heterogeneity in wage flexibility for the nearly 11,000 firms considered in the sample. The authors show that the heterogeneity can be explained by firm size, whether the firm is private or public, and by industry. The authors also document a clear seasonal pattern for changes in wages, clustered in January and October.[6]

Sigurdsson and Sigurdardottir (2012) found similar results by conducting an empirical analysis using monthly administrative data for Iceland between 1998 and 2010. The authors find evidence of heterogeneity in wage flexibility across industries and occupations and strong support for this heterogeneity based on firm size.[7] Additionally, the authors also show evidence of a seasonal pattern in the changes in wages, with nominal wages tending to increase in January and June.

Complementing these findings, Druant et al. (2012) find evidence of heterogeneity in wage rigidity across sectors based on survey information from the Wage Dynamic Network initiative for 17 European countries. In particular, the authors illustrate that wages change more frequently in construction, for larger firms and where the share of white-collar workers is small while are least frequent in trade and market services. Besides, their findings also suggest that competitive pressures within the sector are not relevant for wage flexibility. Concerning the seasonal pattern of wage changes, the paper documents a clear cluster of firms that change their wages principally in January, followed by a smaller cluster changing their prices in July.[8] Finally, the authors uncover a strong synchronization between price and wage changes.

Research regarding heterogeneity in wages for the USA has been scarce. Nonetheless, Barattieri et al. (2014) documented heterogeneity in the flexibility of wage setting for the USA between 1996 and 2004. Using data for 4-month periods (infra-annual frequency) based on the results of the Survey of Income and Program Participation (SIPP), the authors show that wages are stickier in the manufacturing sector and more flexible in agriculture, mining, and services. Similarly, wages are less flexible for workers in managerial occupations compared with workers in direct production. As in other studies, the authors uncover empirical evidence of a seasonal pattern in the frequency of wage adjustments—that the frequency of wage changes is slightly higher in the second half of the year, and that the hazard function of a nominal wage is not constant, having a peak at 12 months. This behavior of the hazard function contradicts the Calvo framework.

Studies that include wage heterogeneity in macroeconomic models complement the evidence mentioned above. Particularly with respect to the seasonal pattern, Olivei and Tenreyro (2007) use a VAR model and find that in quarters where wages are more flexible (third and fourth), the responses of GDP and GDP deflator after a monetary shock are weaker than in quarters where wages are less flexible. In contrast to traditional specifications within the Calvo framework, Olivei and Tenreyro (2007) assume that the probability of resetting wages is different in each quarter (calibrating this probability according to the empirical data for the USA). The authors show that this extended DSGE model

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generates impulse responses that quantitatively match those found in the actual data. In contrast to Olivei and Tenreyro (2007), where the seasonal heterogeneity is addressed, Dixon and Bihan (2012) investigate the effects of heterogeneity in the rigidity of wages across industries. Using data from France, the authors calibrate two independent variations for nominal rigidities: a so-called Generalized Taylor Economy (GTE), where firms have wage spells of different durations, and a Generalized Calvo Economy (GCE), where firms have different probabilities of resetting their wage (price). As the authors highlight, these two mechanisms *allow the distribution of durations implied by the pricing model to be exactly the same as the distribution found in the actual micro-data.* Dixon and Bihan (2012) find that after including these general specifications, the model can replicate the persistence of inflation and output observed in data. The authors also show that the GTE specification can generate a hump-shaped response of inflation and output that is not present in the standard Calvo framework—but widely observed in Business Cycle data.

Pfajfar and de Ridder (2017) found that heterogeneity in the rigidity of nominal wages across US states has important effects on the propagation of monetary and fiscal shocks. Using microdata from the Current Population Survey, the authors calculate state-level downward nominal wage rigidity between 1980 and 2007 finding that, in states with a high degree of wage rigidity, contractionary monetary policy and tax shocks increase unemployment and decrease economic activity to a larger extent compared to states with more flexible wages. Intriguingly, the authors found an asymmetry in the effect of wage rigidities on the impact of shocks. Specifically, Pfajfar and de Ridder (2017) found that the degree of wage rigidity only affects contractionary shocks while the expansionary ones have little effect on real variables.

3. WAGE RIGIDITY AND BUSINESS CYCLES

Several studies highlight the importance of staggered wage adjustments—alongside nominal price rigidities—in explaining business cycle data.[9] For instance, Christiano et al. (1999) and Christiano et al. (2005) document that real wages are acyclical—or at best slightly procyclical, implying that any NK model with nominal price frictions is consistent with business cycle real-wage data if it incorporates nominal wage rigidities. Similarly, Christiano et al. (1999) criticize sticky-price flexible wage models because they imply an implausibly sharp real-wage decline after a negative monetary shock. Furthermore, Christiano et al. (2005), Altig et al. (2002), and Smets and Wouters (2007) find out that models that incorporate both wage and price stickiness do a better job fitting the impulse responses—observed in the data—following a monetary shock.

Regarding the persistence, Andersen (1998) and Huang and Liu (1999) have argued that sticky wages generate more persistent real effects after a monetary perturbation compared to models of sticky prices. Finally, the model with both wage and price stickiness can capture richer wage dynamics vis-à-vis a model with flexible wages.[10]

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These arguments rationalize the incorporation of nominal wage frictions in an NK DSGE framework alongside incomplete nominal price adjustments. In this paper, we aim to model and estimate business cycle implications of the heterogeneity in simultaneous nominal adjustment frictions in wages and prices.

4. THE MODEL

Let us consider the following NK Economy. There are three types of agents: households, firms, and a monetary authority. Firms and households interact in a framework of monopolistic competition in labor provision and production. There is heterogeneity in the way firms set their prices and the households set their wages. Specifically, four different rules for setting prices and wages are considered among firms as well as among households. This contrasts with traditional specifications used, for example, in Smets and Wouters (2007), where staggered price and wage setting behavior—a la Calvo (1983)—is homogeneous across all economic agents.

Following Coibion and Gorodnichenko (2011) we assume that firms are divided into four types. Firms following a standard Calvo (1983) scheme, which set their prices by taking into account the likelihood of not being able to re-optimize in the following period. Firms that follow a scheme of *sticky information* a la Mankiw and Reis (2002) and therefore set their prices in every period but do it using an outdated information set. Firms with *flexible prices*, which set prices optimally in every period; and finally, firms following a *rule-of-thumb* which set prices mimicking the aggregate price inflation of the previous period.

We deviate from Coibion and Gorodnichenko (2011) by assuming that the abovementioned four types of rules are also present in the case of wage setting among a distribution of heterogeneous household/workers who offer differentiated labor services to firms. This specification, therefore, makes it possible to encompass the heterogeneity in price and wage setting behavior simultaneously—as observed in the empirical data, which we discussed in the previous section.

The key features of our model are presented below.[11]

4.1. Firms

There is a continuum of firms indexed by $i \in [0, 1]$, producing differentiated products using the following decreasing returns to scale production function,

$$Y_t(i) = A_t N_t(i)^{1-\alpha}.$$

Firms share the same total productivity, which in log terms follows the AR(1) process $a_t = \rho_a a_{t-1} + \epsilon_t^a$. In this setup $(1 - \alpha)$ represents the elasticity of production with respect to labor, while

$$N_t(i) = \left(\int_0^1 N_t(i,j)^{\frac{\epsilon_w - 1}{\epsilon_w}} dj \right)^{\frac{\epsilon_w}{\epsilon_w - 1}}$$

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corresponds to an index of labor input, with $N_t(i,j)$ being the demand of labor type j by firm i and ϵ_w measures the elasticity of substitution between labor types. The labor types, which will be defined below, belong to households differing in their wage setting rules—with sticky wages, sticky information in wages, flexible wages, and full indexed wages. It should be noted that, in this model, each firm uses all types of labor. Standard first-order conditions to the end of the production factor yield the demand for a particular type of labor as

$$N_t(i,j) = N_t(i)\left(\frac{W_t(j)}{W_t}\right)^{-\epsilon_w},$$

where $W_t(j)$ is the wage paid to that labor type, while the aggregate wage rate is defined as

$$W_t = \left(\int_0^1 W_t(j)^{1-\epsilon_w} dj\right)^{\frac{1}{1-\epsilon_w}}.$$

Firms use their monopolistic power to set product prices. To model the heterogeneity in the price setting behavior, we assume that there are four different "sectors" of the economy and that each sector sets the price of its product following a different rule. In particular, two sectors face rigidities: a fraction s^p_{sp} of firms follows a Calvo pricing mechanism (*sticky prices*), while a fraction s^p_{si} follows a *sticky information* approach. Additionally, a fraction s^p_{fl} of firms sets prices in a *flexible* way, while a share s^p_{rot} of firms adjusts prices following a *rule-of-thumb* approach. Within the latter group, firms set prices according to the price inflation observed in the previous period.

4.1.1. Sticky prices. In the sector with sticky prices, firms follow a Calvo pricing mechanism. This means that in each period the probability of changing prices is $(1-\theta_{cp})$, where θ_{cp} is the probability of being unable to do so. The objective of these firms is to maximize the present value of their profits (1), with respect to the optimal price P_t^{*sp},

$$\sum_{k=0}^{\infty} \theta_{cp}^k E_t\left[Q_{t,t+k}\left(P_t^{*sp} Y(i)_{t+k|t} - \Psi(i)_{t+k}\left(Y(i)_{t+k|t}\right)\right)\right], \tag{1}$$

where $Q_{t,t+k}$ is the stochastic discount factor (see the household problem below) and $\Psi(i)_{t+k}$ is the total nominal cost. Firms optimize subject to the demand for their product, which is given by

$$Y(i)_{t+k|t} = C_{t+k}\left(\frac{P_t^{*sp}}{P_{t+k}}\right)^{-\epsilon_p},$$

where ϵ_p measures the elasticity of substitution between products and C_t is aggregate consumption.[12] The solution to this problem yields the following optimal pricing rule:

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$$P_t^{*sp} = \frac{\epsilon_p}{\epsilon_p - 1} \frac{\sum_{k=0}^{\infty} \beta^k \theta_{cp}^k E_t \left[C_{t+k}^{1-\sigma} P_{t+k}^{\epsilon_p} \psi(i)_{t+k|t} \right]}{\sum_{k=0}^{\infty} \beta^k \theta_{cp}^k E_t \left[C_{t+k}^{1-\sigma} P_{t+k}^{\epsilon_p - 1} \right]},$$

where $\psi_{t+k|t}$ is the nominal marginal cost. After log-linearization, the following equation is obtained (hereafter, small caps represent the log of the variables and variables without time index represent steady-state values):

$$p_t^{*sp} = \mu_p + (1 - \beta\theta_{cp}) \sum_{k=0}^{\infty} \beta^k \theta_{cp}^k E_t \left[mc(i)_{t+k|t} + p_{t+k} \right], \tag{2}$$

where $mc(i)_{t+k|t}$ is the log of the real marginal cost for firm i, and $\mu_p = -mc = \frac{1}{\epsilon_p - 1}$. In equation (2) the optimal price depends on the real marginal cost of a particular firm, which is different from the aggregate real marginal cost given that the production function exhibits decreasing return to scale. It is possible to re-write (2) as a function of the average real marginal cost of the whole economy; therefore, yielding

$$p_t^{*sp} = (1 - \beta\theta_{cp}) \sum_{k=0}^{\infty} \beta^k \theta_{cp}^k E_t \left[\Theta \widehat{mc}_{k+t} + p_{k+t} \right] \tag{3}$$

with $\widehat{mc}_{k+t} = mc_{t+k} - mc$ and $\Theta = \frac{\alpha - 1}{\alpha - \alpha\epsilon_p - 1}$. The aggregate price in this sector is then expressed by

$$P_t^{sp} = \left(\theta_{cp} P_{t-1}^{sp}(i)^{1-\epsilon_p} + (1 - \theta_{cp}) \left(P_t^{*sp} \right)^{1-\epsilon_p} \right)^{\frac{1}{1-\epsilon_p}}, \tag{4}$$

where it is clear that firms that do not optimize in a given period leave their prices unchanged. Equation (4) can be used to calculate the log-linear version of price inflation in this sector as

$$\pi_t^{p,sp} = (1 - \theta_{cp}) \left(p_t^{*sp} - p_{t-1}^{sp} \right).$$

Then, using the optimal price found in equation (3), we get

$$\pi_t^{p,sp} = \beta E_t \left[\pi_{t+1} \right] + \frac{(\theta_{cp} - 1)}{\theta_{cp}} \Theta (\beta\theta_{cp} - 1) \widehat{mc}_t,$$

or in terms of the output gap $\widetilde{y}_t = y_t - y_t^n$, where the superscript n denotes variables in their natural level without nominal rigidities, and the real wage gap ($\widetilde{\omega}_t = \omega_t - \omega_t^n$):

$$\pi_t^{p,sp} = \beta E_t \left[\pi_{t+1}^p \right] - \frac{\left(\theta_{cp} - 1 \right)}{\theta_{cp}} \frac{(\alpha - 1) \left(\beta\theta_{cp} - 1 \right) \widetilde{\omega}_t}{\left(1 - \alpha + \alpha\epsilon_p \right)} + \frac{\left(\theta_{cp} - 1 \right)}{\theta_{cp}} \frac{\alpha \left(\beta\theta_{cp} - 1 \right) \widetilde{y}_t}{\left(1 - \alpha + \alpha\epsilon_p \right)}. \tag{5}$$

Equation (5) corresponds to the standard NK Philips curve.

4.1.2. Sticky information. Following Mankiw and Reis (2002), in a given period only a fraction $(1 - \theta_{ip})$ of the firms in the *sticky information* sector update their

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information, while the remaining θ_{ip} fraction does not, so the new information takes time to reach all firms. In this scenario, the aggregate price for the sector is

$$p_t^{si} = \sum_{j=0}^{\infty}(1-\theta_{ip})\theta_{ip}^{j} p_{t-j,t}^{si}, \tag{6}$$

where $p_{t-j,t}^{si}$ is the price set in period t using the outdated information from $t-j$. Thus, θ_{ip} is a measure of the degree of information stickiness in the sectors, that is, if $\theta_{ip}=0$, no firms use old information.

Denoting $\left\{P_{t,t+k}^{si}\right\}_{k=0}^{\infty}$ as the future prices for a firm, which revises its price plan in period t, the problem of this firm is to choose a price plan that maximizes

$$\sum_{k=0}^{\infty}\theta_{ip}^{k}E_t\left\{Q_{t,t+k}\left(P_{t,t+k}^{si}Y(i)_{t+k}-\Psi(i)_{k+t}\left(Y(i)_{t+k}\right)\right)\right\},$$

subject to the demand for its product,

$$Y(i)_{t+k} = C_{t+k}\left(\frac{P_{t,t+k}^{si}}{P_{t+k}}\right)^{-\epsilon_p}.$$

The solution to this problem is of the form

$$P_{t,t+k}^{si} = \frac{\epsilon_p}{\epsilon_p-1}E_t\left[MC(i)_{t+k}+P_{t+k}\right],$$

for $k=0,1,2,\ldots$. Log-linearization yields

$$p_{t,t+k}^{si} = E_t\left[p_{t+k}-\frac{(\alpha-1)\widehat{mc}_{t+k}}{\alpha\epsilon_p-\alpha+1}\right],$$

which, together with the aggregate price for this sector (equation (6)), provides us with the inflation rate in the sector with information stickiness:

$$\pi_t^{p,si} = \frac{1-\theta_{ip}}{\theta_{ip}}\sum_{j=1}^{J}\theta_{ip}^{j}E_{t-j}\left[\frac{\alpha\Delta\widetilde{y}_t-(\alpha-1)\Delta\widetilde{\omega}_t}{\alpha(\epsilon_p-1)+1}+\pi_t^{p}\right] + \frac{1-\theta_{ip}}{\theta_{ip}}\frac{(\alpha\widetilde{y}_t-(\alpha-1)\widetilde{\omega}_t)}{(\alpha(\epsilon_p-1)+1)}. \tag{7}$$

According to equation (7), price inflation for firms with informational frictions is a weighted sum of expectations of the current price inflation for up to J past periods, changes in the real wage gap, and changes in the output gap. To make this specification implementable, we set $J=8$.[13]

4.1.3. Flexible price sector. In the flexible price sector, all firms optimize prices in every period. In this case, each firm has a one-period objective function and the optimal price in log terms is given by $p_t^{*}=mc(i)_t-mc+p_t$, while the sectoral inflation is

$$\pi_t^{p,fl} = p_t^{*fl}-p_{t-1}^{fl}.$$

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After some algebra and by using $mc(i)_t = mc_t + \frac{\alpha\epsilon_p\left(p_t^{*fl} - p_{k+t}^{fl}\right)}{\alpha - 1}$ and $\widehat{mc}_t = mc_t - mc = \frac{\alpha\widetilde{y}_t}{\alpha - 1} - \widetilde{\omega}_t$, we derive the sectoral inflation rate as

$$\pi_t^{p,fl} = \pi_t^p - \frac{(\alpha - 1)\widetilde{\omega}_t}{\alpha\epsilon - \alpha + 1} + \frac{\alpha\widetilde{y}_t}{\alpha\epsilon - \alpha + 1}. \tag{8}$$

4.1.4. Rule-of-thumb firms. Firms in the rule-of-thumb sector set their prices according to the prevailing price inflation rate in the previous period. Therefore, the inflation rate in this sector is simply given by

$$\pi_t^{p,rot} = \pi_{t-1}^p.$$

4.1.5. Aggregate price inflation. Aggregate inflation is the weighted average of the inflation prevailing in each sector:

$$\pi_t^p = s_{sp}^p \pi_t^{p,sp} + s_{si}^p \pi_t^{p,si} + s_{fl}^p \pi_t^{p,fl} + s_{rot}^p \pi_t^{p,rot}. \tag{9}$$

It is worth to mention that in our framework sectoral inflation rates are dependent on the aggregate price inflation.[14]

4.2. Households

There is a continuum of household/workers indexed by $j \in [0, 1]$ who maximize their utility given by

$$E_0\left[\sum_{t=0}^{\infty} \beta^t U(C_t(j), N_t(j))\right].$$

The instantaneous utility of each household is represented by

$$U(C_t, N_t) = \frac{C_t^{1-\sigma}}{1 - \sigma} - \frac{N_t^{1+\phi}}{1 + \phi}, \tag{10}$$

where σ and ϕ denote the inverse elasticity of intertemporal substitution and the Frisch elasticity of labor supply, respectively. Households value a consumption index given by

$$C_t(j) = \left(\int_0^1 C_t(i, j)^{\frac{\epsilon_p - 1}{\epsilon_p}} di\right)^{\frac{\epsilon_p}{\epsilon_p - 1}}.$$

The consumption decision is a standard two-stage problem where in the first stage each household's demand for a variety j is given by $C_t(i, j) = C_t(j)\left(\frac{P_t(i)}{P_t}\right)^{-\epsilon_p}$ with $P_t = \left(\int_0^1 P_t(i)^{1-\epsilon_p} di\right)^{\frac{1}{1-\epsilon_p}}$. In the second stage the household maximizes its utility function with respect to the consumption index and labor subject to the budget constraint $P_t C_t(j) + Q_t B_t \leq B_{t-1} + W_t N_t + T_t$, where B_{t-1} is the number of bonds

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purchased in the previous period, $Q_t = \frac{1}{1+i_t}$ is the price of the bond, and T_t is a lump-sum transfer representing taxes and dividends.[15]

The solution to the second-stage problem yields the standard first-order conditions, which in log terms are expressed as

$$w_t - p_t = \sigma c_t + \phi n_t, \tag{11}$$

$$c_t = E_t\left[c_{t+1}\right] - \frac{1}{\sigma}\left(i_t - E_t\left[\pi^p_{t+1}\right] - \rho\right), \tag{12}$$

where $i_t = -\ln Q_t$ and $\rho = -\ln \beta$.

Given that households have monopolistic power over their differentiated labor they can set their wage rate. By analogy to the case of the price setting behavior of firms, we assume heterogeneity in wage setting where different fractions of households set their wages following different types of rules. Specifically, a fraction s^w_{sp} of all households follows a Calvo mechanism (*sticky wages*) while another fraction s^w_{si} follows a *sticky information* approach. Additionally, a fraction s^w_{fl} is allowed to set *flexible* wages while the remaining s^w_{rot} adjust wages according the rate of wage inflation observed in the previous period. We label this latter group as *rule-of-thumb* households.

4.2.1. Sticky wages. Following a Calvo scheme, in every period only a fraction $(1-\theta_{cw})$ of the households in the sticky wage sector can change their wages while the remaining θ_{cw} fraction keeps the same wage as in the previous period. That means the household maximizes

$$E_t\left[\sum_{k=0}^{\infty}\beta^k\theta^k_{cw}U(C_{t+k|t}, N_{t+k|t})\right],$$

with respect to W^{*sw}_t subject to the constraints given by the demand for labor and the budget constraint,

$$N(j)_{t+k|t} = \left(\frac{W^{*sw}_t}{W_{t+k}}\right)^{-\epsilon_w} N_{t+k},$$

$$P_{t+k}C_{t+k|t} + E_{t+k}\left[Q_{t+k,t+k+1}D_{t+k+1|t}\right] \leq D_{t+k|t} + W^{*sw}_t N_{t+k|t} - T_{t+k}.$$

The solution to this problem is

$$W^{sw*}_t = \frac{\epsilon_w}{\epsilon_w - 1}\frac{\sum_{k=0}^{\infty}E_t\left[u_c\beta^k N_{t+k}\theta^k_{cw}MRS_{t+k|t}W^{\epsilon_w}_{t+k}\right]}{\sum_{k=0}^{\infty}E_t\left[\frac{u_c\left(\beta^k N_{t+k}\theta^k_{cw}W^{\epsilon_w}_{t+k}\right)}{P_{t+k}}\right]},$$

where $MRS_t = -\frac{u_N}{u_c}$ is the marginal rate of substitution. In log terms, the equation for the optimal wage in the sticky wage sector then becomes

$$w^{*sw}_t = (1-\beta\theta_{cw})\left(w_t - \frac{\widehat{\mu}_{w,t}}{\phi\epsilon_w + 1}\right) + \beta\theta_{cw}E_t w^{*sw}_{t+1},$$

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with $\widehat{\mu}_{w,t} = \mu_{w,t} - \mu_w$ and $\mu_{w,t} = (w_t - p_t) - mrs_t$. We can express the wage inflation for this sector as in the following:

$$\pi_t^{w,sw} = \beta E_t\left[\pi_{t+1}^w\right] - \frac{(\theta_{cw}-1)}{\theta_{cw}}\frac{\widetilde{\omega}_t\,(\beta\theta_{cw}-1)}{(\phi\epsilon_w+1)} + \frac{(\theta_{cw}-1)}{\theta_{cw}}\frac{\widetilde{y}_t(\alpha\sigma-\sigma-\phi)\,(\beta\theta_{cw}-1)}{(\alpha-1)\,(\phi\epsilon_w+1)}.$$

4.2.2. Sticky information in wages. With sticky information in wages, the household chooses the following wage path:

$$w_{t,t+k}^{si} = E_t\left[w_{t+k} - \frac{\widehat{\mu}_{w,t+k}}{\phi\epsilon_w+1}\right],$$

yielding an aggregate wage rate for the sector as

$$w_t^{si} = \sum_{j=0}^{\infty}(1-\theta_{iw})\,\theta_{iw}^j w_{t-j,t}^{si},$$

which allows us to calculate the wage inflation for the sticky information sector as

$$\pi_t^{w,si} = \frac{1-\theta_{iw}}{\theta_{iw}}\sum_{j=1}^{J}E_{t-j}\theta_w^j\left[\pi_t^w + \frac{\Delta\widetilde{y}_t((\alpha-1)\sigma-\phi)-(\alpha-1)\Delta\widetilde{\omega}_t}{(\alpha-1)\,(\phi\epsilon_w+1)}\right] + \frac{(1-\theta_{iw})}{\theta_{iw}}\frac{(\widetilde{y}_t((\alpha-1)\sigma-\phi)-(\alpha-1)\widetilde{\omega}_t)}{((\alpha-1)\,(\phi\epsilon_w+1))}. \quad (\mathbf{13})$$

According to equation (13), wage inflation for households with informational frictions is a weighted sum of expectations of the current wage inflation for up to J past periods, changes in the real wage gap, and in the output gap. As in the case of sticky information in prices we set $J = 8$.

4.2.3. Flexible wages sector. To calculate the optimal wage in the flexible wage sector, the most straightforward procedure is to solve an objective similar to the one with sticky wages but by acknowledging that the objective is now a one-period program. The solution to this program yields the following wage inflation for the flexible wages sector:

$$\pi_t^{w,fl} = \pi_t^w + \frac{\widetilde{y}_t(\alpha\sigma-\sigma-\phi)}{(\alpha-1)\,(\phi\epsilon_w+1)} - \frac{\widetilde{\omega}_t}{\phi\epsilon_w+1}. \quad (\mathbf{14})$$

4.2.4. Rule-of-thumb wages. In the rule-of-thumb wages sector, households set their wages according to the wage inflation rate observed in the previous period. Therefore, the wage inflation in this sector is simply given by

$$\pi_t^{w,rot} = \pi_{t-1}^w.$$

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4.2.5. Aggregate wage inflation. Analogously to the price case, the aggregate wage inflation is computed as the weighted average of the sectoral wage inflations[16]:

$$\pi_t^w = s_{sp}^w \pi_t^{w,sp} + s_{si}^w \pi_t^{w,si} + s_{fl}^w \pi_t^{w,fl} + s_{rot}^w \pi_t^{w,rot}.$$

4.3. Monetary Authority

Following Galí (2008), we assume that the policy rule is such that the monetary authority takes into account and responds to the deviations of output from its natural level and also to the evolution of price and wage inflation. In this respect, the nominal interest rate is given by

$$i_t = \lambda i_{t-1} + (1-\lambda)\left(\rho + \phi_p \pi_t^p + \phi_w \pi_t^w + \phi_y \widetilde{y}_t\right) + \nu_t, \tag{15}$$

where the disturbance term is an AR(1) process with $\nu_t = \epsilon_t^\nu$. The parameter λ captures the degree of interest rate smoothing.[17]

4.4. Equilibrium Conditions

The derivation of the IS curve completes the model. This relation is derived, in output gap terms, using the Euler equation of the household (12) together with the market clearing condition $y_t = c_t$. The IS equation then gets expressed as

$$\widetilde{y}_t = -\frac{1}{\sigma}\left(i_t - E_t\left[\pi_{t+1}^p\right] - r_t^n\right) + E_t\left[\widetilde{y}_{t+1}\right], \tag{16}$$

where the output gap—$\widetilde{y}_t = y_t - y_t^n$—is measured with respect to the natural output and the production level prevailing in the absence of nominal rigidities is given by $y_t^n = \psi_{ya}^n a_t + \vartheta_y^n$, with $\psi_{ya}^n = \frac{1+\phi}{\sigma(1-\alpha)+\phi+\alpha}$ and $\vartheta_y^n = -\frac{(1-\alpha)(\mu_p - ln(1-\alpha))}{(1-\alpha)\sigma+\phi+\alpha}$.

Additionally, the natural interest rate is defined as $r_t^n = \rho + \sigma \psi_{ya}^n E_t \Delta a_{t+1}$, while the natural wage follows $w_t^n = \psi_{wa}^n a_t + \vartheta_w^n$, where $\psi_{wa}^n = \frac{1-\alpha\psi_{ya}^n}{1-\alpha}$ and $\vartheta_w^n = \frac{(\mu_p - ln(1-\alpha))(\alpha\sigma-\sigma-\phi)}{\phi-\alpha\sigma+\alpha+\sigma}$. Finally, wage and price inflations are linked according to $w_t = w_{t-1} + \pi_t^w - \pi_t^p$. The complete model consists of 18 endogenous variables ($\widehat{y}_t$, y_t^n, y_t, r_t^n, n_t, π_t^p, π_t^w, w_t, w_t^n, i_t, $\pi_t^{p,sp}$, $\pi_t^{p,si}$, $\pi_t^{p,fl}$, $\pi_t^{p,rot}$, $\pi_t^{w,sp}$, $\pi_t^{w,si}$, $\pi_t^{w,fl}$, $\pi_t^{w,rot}$), 26 parameters (σ, α, ρ, ϕ_p, ϕ_w, ϕ_y, ρ_a, ρ_ν, σ_a, σ_ν, β, θ_{cp}, θ_{ip}, ϵ_p, θ_{cw}, θ_{iw}, ϵ_w, ϕ, λ, s_{sp}^p, s_{si}^p, s_{fl}^p, s_{sp}^w, s_{si}^w, s_{fl}^w, μ_p) and two exogenous processes (a_t and ν_t). A list of all the equations of the model is available in the supplemental online appendix.

5. EMPIRICAL ANALYSIS

In order to investigate the empirical implications of the heterogeneity in wage and price setting behavior, we estimate the model using Bayesian techniques. We utilize the Bayesian estimation methodology because of the well-known advantages of this full information procedure over other estimation methods. On the one hand, Bayesian techniques allow performing the estimation using pre-sample

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information stemming from data or past research. The pre-sample information, which is included in the estimation procedure as priors for the distribution of the parameters, is difficult to accommodate in classical estimation methodologies like Maximum Likelihood or Generalized Method of Moments. The pre-sample information is highly valuable because it helps to improve the identification of the parameters [DeJong et al. (2000)]. On the other hand, Bayesian methodology, being a full information procedure, appears more appealing than procedures based on limited information such as the Simulated Method of Moments [McFadden (1989)] or a calibration exercise. The advantage over the former is that because Simulated Method of Moments is based only on a limited number of moments, and the disadvantage of calibration is that it lacks a formal statistical foundation [Kim and Pagan (1999)].

At an arguably deeper level, the main advantage of the Bayesian approach is its direct quantification of uncertainty. In other words, the Bayesian approach helps to make transparent the fact that in essence, all models are false. The Bayesian approach, therefore, takes into account the uncertainty associated with the parameters of the model and with the possible misspecification of the model itself. This in turn, as discussed by Gelman et al. (2013), facilitates the fitting to data of complicated models with several parameters and multilayer probability specifications. Also, but not less important, given that in the Bayesian approach the parameters to be estimated are random variables, the "confidence intervals" have an intuitive interpretation that contrasts with that provided in the frequentist paradigm.[18]

We estimate the benchmark model with heterogeneity in prices and wages (hereafter the HpHw model) based on the standard priors used in the literature (Table 1). Specifically, mean, standard error, and the distribution for the elasticity of production with respect to labor $(1-\alpha)$, the parameters governing the reaction of the monetary policy with respect to the output gap (ϕ_y), to price inflation (ϕ_p), and the degree of interest rate smoothing (λ) were set according to Smets and Wouters (2007). The standard error and the distribution for the inverse of the elasticity of intertemporal substitution (σ) are also based on Smets and Wouters (2007). The prior mean for this parameter, however, was set according to Galí (2008) who assumes log-utility for consumer's preferences. Regarding the standard deviation of technology and policy shocks as well as the standard deviation of the measurement errors in the output gap and in wage inflation we take the priors from Rabanal and Rubio-Ramírez (2001). The parameters measuring the degree of price and wage stickiness a la Calvo (θ_{cp} and θ_{cw}) follow a Beta distribution with a mean that incorporates the finding in the literature that wages tend to be less flexible than prices. By symmetry, the priors for the parameters governing information rigidity in prices and wages (θ_{ip} and θ_{iw}) were set alike the Calvo case. Similarly, the autoregressive parameter for the evolution of the technology process (ρ_a) has the first and second moments as in Smets and Wouters (2007). Finally, the population share of each sector—with respect to price and wage setting behavior—is assumed to be equal to 0.25 with standard deviations of 0.15.[19] We do not estimate some of the parameters because they present problems for

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TABLE 1. Priors

Parameter	Distribution	Mean	Standard error
β	Fixed	0.99	–
σ	Gamma	1	0.375
ϕ	Fixed	1	–
α	Normal	0.3	0.05
ϵ_w	Fixed	10	–
ϵ_p	Fixed	10	–
θ_{cw}	Beta	0.75	0.1
θ_{cp}	Beta	0.6	0.1
θ_{iw}	Beta	0.75	0.1
θ_{ip}	Beta	0.6	0.1
ϕ_p	Normal	1.5	0.25
ϕ_w	Normal	0.5	0.05
ϕ_y	Normal	0.12	0.05
ρ_a	Beta	0.5	0.2
s^p_{sp}	Beta	0.25	0.15
s^p_{si}	Beta	0.25	0.15
s^p_{fl}	Beta	0.25	0.15
s^w_{sp}	Beta	0.25	0.15
s^w_{si}	Beta	0.25	0.15
s^w_{fl}	Beta	0.25	0.15
λ	Beta	0.75	0.1
σ_a	Inverse Gamma	0.005	∞
σ_v	Inverse Gamma	0.005	∞
σ_y^{me}	Inverse Gamma	0.002	∞
$\sigma_{\pi_w}^{me}$	Inverse Gamma	0.002	∞

Notes: The parameters are: Discount factor (β), Frish elasticity (ϕ), inverse of the elasticity of intertemporal substitution (σ), elasticity of production with respect to labor ($1-\alpha$), elasticity of substitution for products (ϵ_p), elasticity of substitution for labor types (ϵ_w), rigidity in wages a la Calvo (θ_{cw}), rigidity in prices a la Calvo (θ_{cp}), information rigidity in wages (θ_{iw}), information rigidity in prices (θ_{ip}), reaction to price inflation (ϕ_p), reaction to wage inflation (ϕ_w), reaction to output gap (ϕ_y), persistence for technology process (ρ_a), nominal interest rate smoothing (λ), share of firms with sticky prices (s^p_{sp}), share of firms with sticky information in prices (s^p_{si}), share of firms with flexible prices (s^p_{fl}), share of firms with rule-of-thumb prices (s^p_{rot}), share of households with sticky wages (s^w_{sp}), share of households with sticky information in wages (s^w_{si}), share of households with flexible wages (s^w_{fl}), share of households with rule-of-thumb wages (s^w_{rot}), standard deviation for technology process (σ_a), standard deviation for monetary process (σ_v), standard deviation for measurement error in output gap (σ_y^{me}), and standard deviation for measurement error in wage inflation ($\sigma_{\pi_w}^{me}$).

the identification of our model. To this end, we set the Frisch elasticity of the labor supply (ϕ) to 1 as in Coibion and Gorodnichenko (2011) and the discount factor to 0.99 as in Rabanal and Rubio-Ramírez (2001). Finally, the elasticity of substitution between goods and labor is set according to Smets and Wouters (2007).

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Following the tradition in the literature, we allow for measurement error for output gap and wage inflation.[20] We have a total number of four shocks in the model. Hence, when estimating we use four observed variables: output gap, price inflation, wage inflation, and nominal interest rate. Our sample covers 1955:1 to 2008:4 in quarterly periodicity for the USA. We explicitly excluded the data after 2008, when the zero-lower bound was active, to avoid potential bias in the estimated parameters.[21] Except for the interest rate, we transform all variables using the natural logarithm and detrend them using the method proposed by Hamilton (2017). Specifically, stationarity is obtained by calculating, for a generic variable y_t, $v_{t+h} = y_{t+h} - y_t$ with $h = 8$, given that we have quarterly periodicity.[22] All data observations are from the Federal Reserve Bank of St. Louis database.

In our Bayesian estimation we use one chain—composed of 250,000 draws, 50,000 of which are discarded during the burning period. To check the stability of the chain, Geweke (1999) procedure was implemented. As it can be seen in the supplemental online appendix, all parameters exhibit substantial convergence. The acceptance rate is 24.4%, which is sufficiently close to what it is considered optimal [around one fourth, Koop (2003)].[23] The (theoretical) identification of all structural components is checked using the local identification analysis described by Iskrev (2010).

6. RESULTS

In this section we provide the estimation results for our reference mode and for a variety of alternative models. We also show the impulse responses that allow us to understand the macroeconomic relevance of the heterogeneity in wage setting behavior.

6.1. Estimation Results

Table 2 presents the estimation results for the posterior distributions of the benchmark model with heterogeneity in price and wage setting. In general, our estimates are in line with what other studies have found. For most parameters, the mean and the standard deviation of the prior distribution differ greatly from the corresponding moments of the posterior distribution. This difference is particularly evident for the parameters that measure the share of the different pricing and wage behaviors. A result like this indicates that the data are informative in the estimation of the subsequent distributions.

Regarding the estimated values, the model exhibits a value for the elasticity of intertemporal substitution of 0.21, which is similar to the value found by Rabanal and Rubio-Ramírez (2001) and in between what was found by Andrés et al. (2005) and Rabanal and Rubio-Ramírez (2005). The elasticity of production with respect to labor $(1 - \alpha)$ closely matches the values previously estimated in the literature for the USA. Although we used different priors when estimating the degrees of price and wage stickiness a la Calvo, the estimated values end up being very

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TABLE 2. Estimated values for the HpHw model

Parameter	Mean	Standard Deviation	LB	UB
σ	4.760	0.450	4.133	5.449
α	0.386	0.050	0.303	0.467
θ_{cw}	0.747	0.100	0.590	0.910
θ_{cp}	0.743	0.048	0.664	0.821
θ_{iw}	0.786	0.098	0.636	0.941
θ_{ip}	0.617	0.091	0.466	0.766
ϕ_p	1.505	0.218	1.138	1.852
ϕ_w	0.477	0.051	0.392	0.559
ϕ_y	0.106	0.049	0.029	0.189
ρ_a	0.782	0.032	0.733	0.838
s^p_{sp}	0.846	0.052	–	–
s^p_{si}	0.054	0.032	–	–
s^p_{fl}	0.054	0.026	–	–
s^p_{rot}	0.047	0.020	–	–
s^w_{sp}	0.278	0.177	–	–
s^w_{si}	0.184	0.081	–	–
s^w_{fl}	0.275	0.090	–	–
s^w_{rot}	0.262	0.098	–	–
λ	0.830	0.017	0.802	0.858
σ_a	0.033	0.004	0.027	0.040
σ_v	0.004	0.001	0.004	0.004
σ^{me}_y	0.035	0.002	0.032	0.038
$\sigma^{me}_{\pi_w}$	0.009	0.001	0.008	0.009

Notes: The parameters are: inverse of the elasticity of intertemporal substitution (σ), elasticity of production with respect to labor ($1-\alpha$), rigidity in wages a la Calvo (θ_{cw}), rigidity in prices a la Calvo (θ_{cp}), information rigidity in wages (θ_{iw}), information rigidity in prices (θ_{ip}), reaction to price inflation (ϕ_p), reaction to wage inflation (ϕ_w), reaction to output gap (ϕ_y), persistence for technology process (ρ_a), nominal interest rate smoothing (λ), share of firms with sticky prices (s^p_{sp}), share of firms with sticky information in prices (s^p_{si}), share of firms with flexible prices (s^p_{fl}), share of firms with rule-of-thumb prices (s^p_{rot}), share of households with sticky wages (s^w_{sp}), share of households with sticky information in wages (s^w_{si}), share of households with flexible wages (s^w_{fl}), share of households with rule-of-thumb wages (s^w_{rot}), standard deviation for technology process (σ_a), standard deviation for monetary process (σ_v), standard deviation for measurement error in output gap (σ^{me}_y), and standard deviation for measurement error in wage inflation ($\sigma^{me}_{\pi_w}$). The delta method is used to calculate the standard deviation of the parameters measuring the share of firms and households. LB and UB stand for the Lower Bound and the Upper Bound of the 90% HPD interval.

similar to each other. The average duration of contracts with Calvo is 4 and 3.9 quarters for wages and prices, respectively. These values are comparable to what is usually found in the literature, for example, they are within the boundaries estimated by Christiano et al. (2005). These average durations are also similar to the findings in Smets and Wouters (2007) for wages and the findings in Rabanal and Rubio-Ramírez (2001) for prices. With respect to information rigidity, the estimated values show that this is more pronounced for prices and less pronounced

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for wages compared to the traditional rigidity à la Calvo. In particular, wage and price contracts with informational frictions have average durations of 4.7 and 2.6 quarters, respectively.[24] With regard to the parameter capturing the persistence of the technology disturbance process, the estimated value is in line with the estimates argued by others in the literature. In particular, the technology process shows very high persistence, highly consistent with the findings of Rabanal and Rubio-Ramírez (2005) and Galí (2008).

The estimation results indicate that a majority of the firms (85%) set their prices according to the Calvo rule. This high population estimate for Calvo-pricer firms can be confirmed with the findings of several papers in the literature, such as Klenow and Kryvtsov (2008), Coibion and Gorodnichenko (2011), and Carlsson and Skans (2012). Regarding the Calvo rule, the estimate to the end of households' wage setting behavior is somewhat different: while Calvo-wage setters are also the majority of households, their population ratio (28% of the households) is much lower than that of the Calvo-pricer firms. Both in terms of prices and wages, the share of agents who use the sticky information is relatively small—where the fraction is smaller for price setters (5%) than wage setters (18%). Another interesting estimate that we document is that compared to prices, wages appear to be more flexible given that 27% of households set their wages using the flexible wage setting rule compared to a population ratio of flexible price setter firms of 5%. Finally, the share of the households with indexed wages (26%) is greater than the corresponding fraction for indexed price setters (5%). These findings allow us to argue that regarding modeling heterogeneity of nominal rigidities, households' wage setting heterogeneity is much more prevalent than firms' price setting heterogeneity when estimating an NK model with aggregate data. This means a uniform Calvo price setting rule could be a good representation for firms, but more heterogeneity appears to be relevant to the end of households.

In order to investigate the macroeconomic implications of the heterogeneity in price and wage setting behavior, we estimate five alternative models in addition to the benchmark Heterogeneous-Prices-Heterogenous-Wages (HpHw) model. Specifically, we estimate two models of flexible wage setting—one where heterogeneity in price setting (a model labeled as HpFw) is assumed and another one with only Calvo-type price setting (labeled as CpFw). Additionally, we estimate two other models where wages are set a la Calvo. In one case of this second group, all price setters follow a Calvo scheme as well (labeled as CpCw), and in another case, we allow for heterogeneity in the price setting behavior (labeled as HpCw). Finally, we also estimate a model where prices are flexible while there is heterogeneity in the wage setting behavior (labeled as FpHw). As Table 3 illustrates, the restricted specifications can be derived from the general model by fixing some corresponding parameters.

Table 4 presents the parameter estimates for all six models, which also includes our benchmark with heterogeneity in wage and price setting (HpHw). In general, and despite the differences in specifications, the estimated parameter values are comparable across models. Examples of the parameters that are robust to different

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TABLE 3. Specification for the six models to estimate

	Setting behavior		Shares	
Model	Prices	Wages	Firms	Household
HpHw	Heterogeneity	Heterogeneity	All estimated	All estimated
HpFw	Heterogeneity	Flexible	All estimated	$s^w_{fl} = 1$
CpCw	A la Calvo	A la Calvo	$s^p_{sp} = 1$	$s^w_{sp} = 1$
CpFw	A la Calvo	Flexible	$s^p_{sp} = 1$	$s^w_{fl} = 1$
HpCw	Heterogeneity	A la Calvo	All estimated	$s^w_{sp} = 1$
FpHw	Flexible	Heterogeneity	$s^p_{fl} = 1$	All estimated

Notes: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages. The relevant parameters for this table are: share of firms with sticky prices (s^p_{sp}), share of firms with sticky information in prices (s^p_{si}), share of firms with flexible prices (s^p_{fl}), share of firms with rule-of-thumb prices (s^p_{rot}), share of households with sticky wages (s^w_{sp}), share of households with sticky information in wages (s^w_{si}), share of households with flexible wages (s^w_{fl}), and share of households with rule-of-thumb wages (s^w_{rot}).

specifications are the degree of information stickiness for prices and the parameter measuring the reactions of the monetary policy to changes in the output gap. The stability of the estimates for the elasticity of intertemporal substitution across models with rigidity in prices is also noteworthy. The average duration of price contracts a la Calvo ranges from 1.8 to 3.5 quarters, while for price information rigidities, the interval goes from 2.2 to 2.8 quarters. In this respect, we find that overall, Calvo price stickiness is higher in models that incorporate heterogeneity in prices, and the estimate of this kind of price stickiness becomes higher when the heterogeneity is extended to wages. Average Calvo wage contract duration, in turn, gets estimated values between 2.8 and 6.2 quarters and, as in the case of price duration, it becomes higher once we allow for heterogeneity in the manner in which wages are set. It is also worth noting that even though the priors in the three models that take into account Calvo stickiness in prices and wages (HpHw, CpCw, and HpCw) come along with a greater stickiness in wages than in prices, the estimated posteriors for models CpCw and HpCw show the opposite result. This is in contrast with findings in the literature, for example, Smets and Wouters (2003), Christiano et al. (2005), and Galí et al. (2012), but is in line with the degree of stickiness found, for example, by Rabanal and Rubio-Ramírez (2001, 2005), Rabanal (2007), and De Graeve (2008).

In Table 4 we can also observe that there is a large variance in the parameter estimates measuring the reaction of the monetary policy rule with respect to the changes in price inflation. To this end, it is clear that in models where wages and/or prices are assumed to be flexible, the reaction to price inflation is almost 50% greater than in models where some kind of rigidity is considered in wages.

One of the main advantages of models with nominal rigidity heterogeneity is that they offer the possibility to calculate the shares of each sector—shares (as we documented above) that are not directly observable in the data. In this respect, it is not easy to make an extensive comparison against the findings in the literature due to the scarce availability of papers considering heterogeneity—with the exception

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TABLE 4. Estimated values for the six models

Parameter	HpHw	HpFw	CpCw	CpFw	HpCw	FpHw
σ	4.760	4.055	4.699	4.250	4.559	4.243
α	0.386	0.222	0.358	0.232	0.375	0.372
θ_{cw}	0.747	–	0.639	–	0.640	0.838
θ_{cp}	0.743	0.578	0.684	0.455	0.715	–
θ_{iw}	0.786	–	–	–	–	0.937
θ_{ip}	0.617	0.542	–	–	0.642	–
ϕ_p	1.505	2.049	1.388	2.073	1.453	2.069
ϕ_w	0.477	0.496	0.480	0.500	0.478	0.500
ϕ_y	0.106	0.131	0.081	0.130	0.084	0.119
ρ_a	0.782	0.776	0.856	0.787	0.848	0.994
s^p_{sp}	0.846	0.211	1*	1*	0.821	–
s^p_{si}	0.054	0.367	–	–	0.070	–
s^p_{fl}	0.054	0.288	–	–	0.064	1*
s^p_{rot}	0.047	0.135	–	–	0.045	–
s^w_{sp}	0.278	–	1*	–	1*	0.190
s^w_{si}	0.184	–	–	–	–	0.432
s^w_{fl}	0.275	1*	–	1*	–	0.052
s^w_{rot}	0.262	–	–	–	–	0.326
λ	0.830	0.489	0.836	0.504	0.832	0.799
σ_a	0.033	0.013	0.029	0.012	0.027	0.005
σ_v	0.004	0.009	0.004	0.009	0.004	0.004
σ^{me}_y	0.035	0.033	0.036	0.033	0.036	0.038
$\sigma^{me}_{\pi_w}$	0.009	0.012	0.009	0.013	0.009	0.009
Log marginal density	2746.39	2665.70	2745.36	2657.94	2744.97	2670.93

Notes: *These parameters were not estimated but fixed. second column of this table replicates second column of Table 2. In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.
The parameters are: inverse of the elasticity of intertemporal substitution (σ), elasticity of production with respect to labor ($1-\alpha$), rigidity in wages a la Calvo (θ_{cw}), rigidity in prices a la Calvo (θ_{cp}), information rigidity in wages (θ_{iw}), information rigidity in prices (θ_{ip}), reaction to price inflation (ϕ_p), reaction to wage inflation (ϕ_w), reaction to output gap (ϕ_y), persistence for technology process (ρ_a), nominal interest rate smoothing (λ), share of firms with sticky prices (s^p_{sp}), share of firms with sticky information in prices (s^p_{si}), share of firms with flexible prices (s^p_{fl}), share of firms with rule-of-thumb prices (s^p_{rot}), share of households with sticky wages (s^w_{sp}), share of households with sticky information in wages (s^w_{si}), share of households with flexible wages (s^w_{fl}), share of households with rule-of-thumb wages (s^w_{rot}), standard deviation for technology process (σ_a), standard deviation for monetary process (σ_v), standard deviation for measurement error in output gap (σ^{me}_y), and standard deviation for measurement error in wage inflation ($\sigma^{me}_{\pi_w}$).

of Coibion and Gorodnichenko (2011). Coibion and Gorodnichenko (2011) estimate the population fractions of 62%, 21%, 8%, and 9% for Calvo stickiness, sticky information, flexible, and rule-of-thumb prices, respectively. As we delineated, in our benchmark (HpHw) model estimation, we also find that the majority of the firms follow the Calvo price setting behavior while the share of the firms that face some kind of stickiness in prices (basically the sum of Calvo price setters and sticky information firms) is 90%. Both results are in line with the

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TABLE 5. Model comparison

Model	HpHw	HpFw	CpCw	CpFw	HpCw	FpHw
Priors	0.166	0.166	0.166	0.166	0.166	0.166
Log Marginal Density	2746.39	2665.70	2745.36	2657.94	2744.97	2670.93
Posterior Model Probability	0.627	0	0.222	0	0.151	0

Notes: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

findings of Coibion and Gorodnichenko (2011), where to the end of the latter the cumulative sum of firms which face Calvo and sticky information in Coibion and Gorodnichenko (2011) is 83%. The estimated population shares in the two papers are also similar for the case of flexible prices [5% in our study vs. 8% in Coibion and Gorodnichenko (2011)].

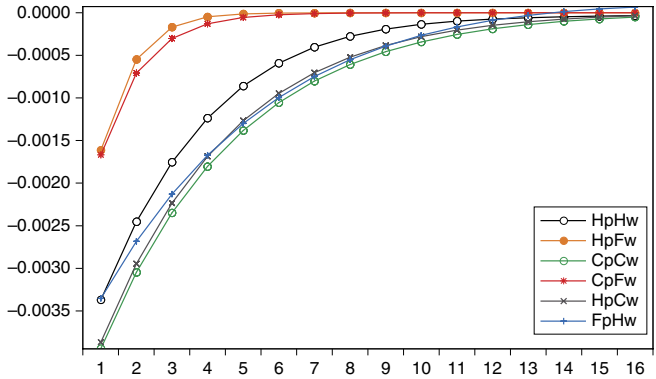
Another result to highlight is the drastic effect of the inclusion of rigidity on the estimated shares in models with heterogeneity in prices. Specifically, comparing the model HpFw with models HpHw and HpCw (a model with flexible wages vs. two models with some kind of rigidity in wages), we can observe that the inclusion of stickiness in wages, irrespective of the presence of heterogeneity in this stickiness, substantially increases the estimated share of firms that follow a sticky price rule. The fact that the data favor a higher share of sticky price firms once sticky wages are included suggests that these two types of nominal rigidities reinforce each other when matching the macroeconomic data—a result that confirms the findings in previous empirical studies such as Druant et al. (2009).

Finally, a basic model comparison regarding the ability of each model to fit the data confirms the usual result in the literature that models which consider only flexible prices or flexible wages are dominated by specifications where those are assumed to be rigid (last row of Table 4). In the same line, the comparison among models reveals that the posterior model probability favors the model which incorporates the simultaneous heterogeneity in price and wage setting behavior (Table 5). Most importantly, the benchmark model HpHw, with heterogeneity in price and wage setting behavior, outperforms the traditional specification with prices and wages a la Calvo (CpCw) in fitting the data.

6.2. Implications of Wage Setting Heterogeneity for Monetary and Technology Shocks

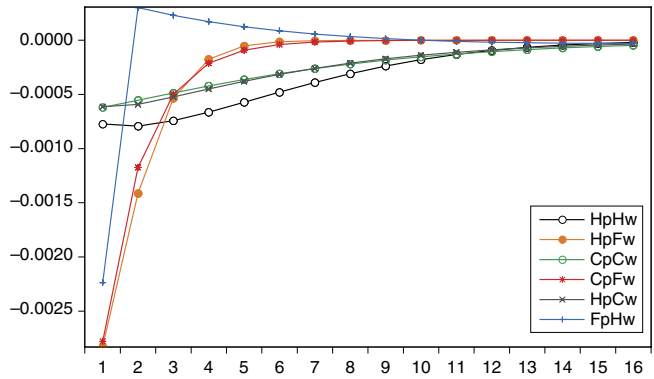
6.2.1. Monetary shocks. Figures 1–4 illustrate the responses of the four key model variables after a positive (tightening) monetary shock using the estimated monetary policy reaction function. For the output gap variable, the six models can

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Note: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 1. IRF for output gap after a monetary shock.



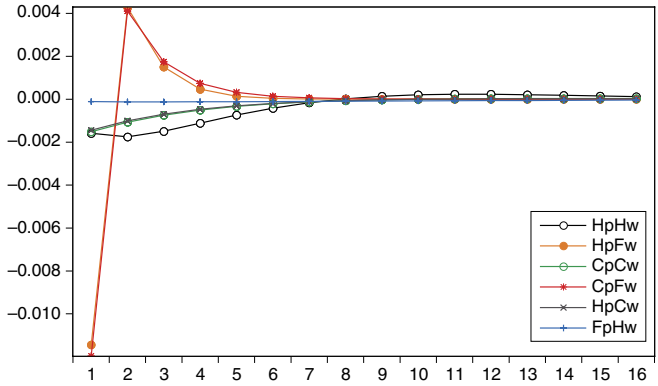
Note: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 2. IRF for price inflation after a monetary shock.

be separated into two broad groups based on the incorporation of nominal wage rigidities. This is somewhat an expected result given that the estimated parameters across models within each group (nominal wage rigidity group vs. flexible wages group) are very similar, in particular the parameters measuring the population fractions of sectors with differing price setting behavior.

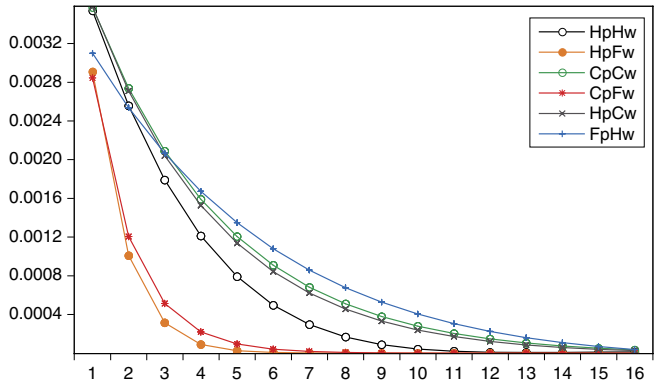
As a key contribution of our analysis, we find that the incorporation of heterogeneity in wage setting behavior yields impulse responses that are different from what one obtains using a more standard model where Calvo-type nominal wage setting is uniform across households. Particularly in models where price

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Note: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 3. IRF for wage inflation after a monetary shock.



Note: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 4. IRF for nominal interest rate after a monetary shock.

setting heterogeneity is present, following a monetary contraction, the output gap contracts less and recovers more quickly in the model with heterogeneous wage setters compared to the model with uniform Calvo-type wage setting.[25]

We also obtain interesting qualitative effects of wage setting heterogeneity on inflation. Specifically, with respect to the nominal price changes, when heterogeneity in wage setting is allowed, the pricing inflation exhibits some level of persistence following a monetary contraction. Such qualitative price inflation persistence cannot be observed in any of the other alternative model specifications. Similarly, following a monetary contraction, the model with wage setting heterogeneity generates wage inflation persistence, too. As a matter of fact, the model

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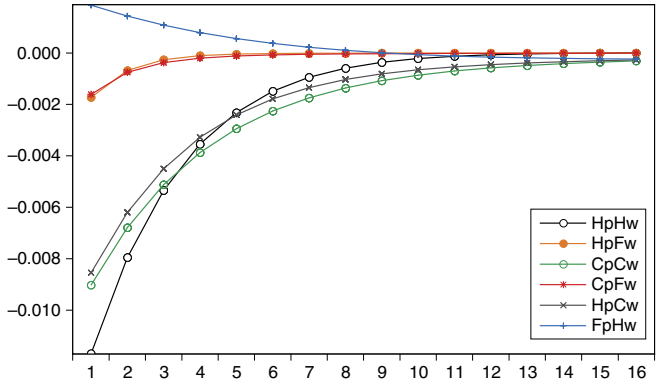
produces initially declining wage inflation and then a follow-up stagnation in wage inflation and then rising wage inflation. None of the alternative models are capable of generating this qualitative cyclical property either. This is an important qualitative result, because inflation persistence is a significant characteristic of the business cycle data as have been highlighted by Rotemberg and Woodford (1997), Christiano et al. (1999), Altig et al. (2002), Rabanal and Rubio-Ramírez (2003), and Christiano et al. (2005) (for prices) and by Edge et al. (2003) (for wages). Using VAR-based approaches these papers find a substantial amount of inertia and persistence in price and wage inflation following monetary contractions and show that to replicate these dynamics, DSGE models should exhibit strong internal propagation mechanisms. In this regard, Christiano et al. (2005) conclude that this propagation mechanism could be achieved by incorporating additional frictions to the standard model, specifically the inclusion of habit formation, adjustment cost in investment, and notably, variable capital utilization. We note that our benchmark model (HpHw) replicates the inertia and persistence of both price and wage inflation without relying on any of those propagation mechanisms.

With respect to the nominal interest rate, the behavior of the setup with heterogeneous wage rigidity shows qualitative similarities with the rest of the sticky wages class of models. To this end, there is a striking quantitative difference though: The model with heterogeneous wage setting produces a nominal interest rate, which reacts to the monetary contraction significantly less compared to the models with standard Calvo-type nominal wage setting.

To the end of the overall nominal wage rigidity, Figure 3 illustrates the implausibly strong reaction of the wage inflation in models with flexible wages which is, as we delineated before, at odds with macro data. This strong reaction is followed by an implausibly large reaction into the opposite direction starting the second period. This effect is more persistent in the models where no heterogeneity in prices is considered because there is not a sector with flexible prices that can be adjusted. The muted behavior of wage inflation in models with sticky wages reduces the implication of the monetary shock for real wages. In this way it helps to counteract (through the marginal cost) the effect of such shocks on inflation resulting from the decline in the output gap. As a result, models with rigid wages exhibit more subtle reactions of price inflation (Figure 2). The lower the reaction of the price inflation, the higher and more persistent response of the nominal interest rate (Figure 4). This property brings as its consequence sharper contractions in output gap following monetary shocks (Figure 1).

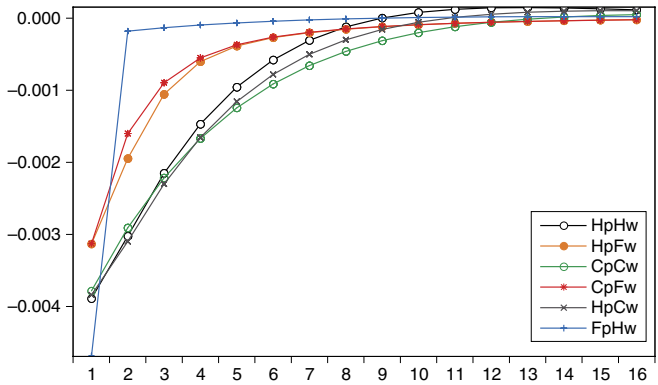
6.2.2. Technology shocks. The responses of the key macro variables following a technology shock are presented in Figures 5–8. As in the case of a monetary shock, the response to a technology shock is differentiated according to the presence of rigidity of nominal wages. It is worth noting that the responses for all variables are more persistent (compared to a monetary shock) given that for all models the estimated value for the persistence of the technology shock (ρ_a) is high. Qualitatively, the wage inflation persistence property of the heterogeneous

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Notes: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 5. IRF for output gap after a technology shock.



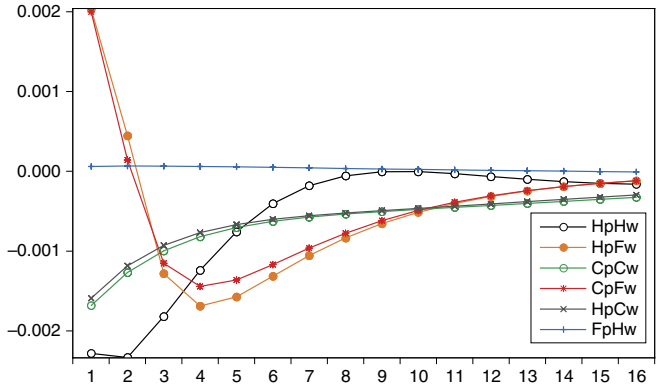
Notes: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 6. IRF for price inflation after a technology shock.

wage setting model is observable following a technology shock as well. Price inflation behavior is comparable across the class models which incorporate nominal wage rigidities. Quantitatively, we obtain that the output gap and the nominal interest rate in the model with heterogeneous wage setting react more compared to the model with standard-Calvo-type nominal wage setting.

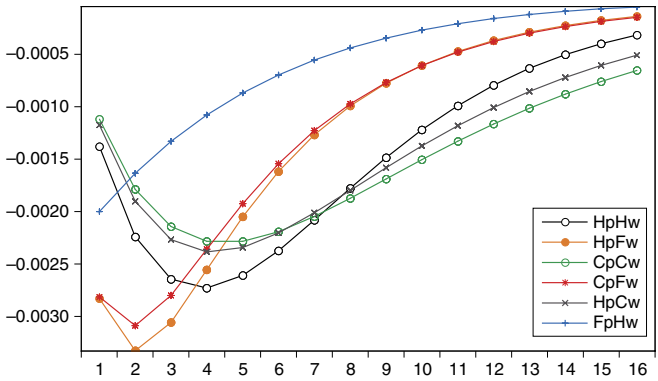
Our results show that incorporating heterogeneity in wage rigidity–in addition to the heterogeneity in price setting–enriches the business cycle implications of a standard NK model qualitative and quantitatively.

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Notes: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 7. IRF for wage inflation after a technology shock.



Notes: In the acronyms of the models: H—Heterogeneity, C—Calvo, F—Flexible, p—Prices, and w—Wages. Then, for example, HpFw corresponds to a model with Heterogeneity in Prices and Flexible Wages.

FIGURE 8. IRF for nominal interest rate after a technology shock.

Figure 5 illustrates a strong decline in the output gap for the three models incorporating nominal rigidities in wages and a comparatively more pronounced decline once heterogeneity in wages is considered (HpHw). This reduction is explained by a strong rise in natural output that is proportionally stronger in the model with heterogeneity in wage setting behavior. This is not a direct result of heterogeneity though, but rather a consequence of the estimated parameter values resulting from the model specification, particularly the lower estimated value of the inverse elasticity of substitution. Unsurprisingly, the output gap is more persistent in models where wages present some degree of rigidity. With respect to the

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price inflation (Figure 6), we can observe that all of the model specifications can capture the fall in price inflation following a technology shock. The response of price inflation (to a technology shock) closely correlates with the response of the output gap, where the response of price inflation to a technology shock is stronger whenever there is a large decline in output gap (except for the model with flexible prices). Figure 7 exhibits a larger variance in the response of wage inflation—with respect to a technology shock—in those models with flexible wages, which is a consequence of the pronounced positive response observed in the first periods—followed by even a more strong decline in wages in between periods three and seven. The dynamics of the nominal interest rate (Figure 8) is in line with the response of the output gap and the inflation in wages and prices. In particular, we can show that the reaction rule of the monetary policy in models with only flexible wages implies a strong reduction of the interest rate two periods following the technology shock in order to compensate for the large and more persistent reductions observed in the wage inflation.

6.3. Conclusions for Monetary Policy and Wage Flexibility

Our analysis builds upon the estimated DSGE model of Coibion and Gorodnichenko (2011) with strategic interaction among heterogeneous price setting by incorporating not only nominal wage rigidities but also heterogeneity in the wage setting behavior. That makes our model more complete and more relevant for analyzing the interaction between price and wage rigidities. Some authors [e.g., Christoffel and Linzert (2010)] separate the production process in two steps with only wage rigidities in the intermediate sector and price rigidities in the final goods sector and thus not allowing for an interaction between price and wage rigidities in the model—unlike our setup.

In our model there is a real interaction between price and wage rigidities—reinforcing the dynamics generated by each type of friction. More price rigidities lead to more wage rigidities and vice versa. Companies have less need to adjust their price setting if wages and their marginal costs change less frequently. Our Impulse Response Functions (IRF) in Figures 1–4 show large differences between flexible and rigid wages as already concluded in the previous section, while the difference between Calvo wages and Heterogeneity in staggered wage adjustment (respectively, Cw and Hw) seems to be less obvious than the difference with flexible wages (Fw). This is from an intuitive point of view quite understandable.

On the basis of the IRF for the output gap after a monetary shock in Figure 1 and the IRF for price inflation after a monetary shock in Figure 2, we may conclude that given price rigidities it matters a lot for monetary policy whether there are wage rigidities or not. If wages are flexible, monetary policy is much more effective than if wages are sticky. In the case of wage flexibility the costs of monetary policy in terms of the output gap are also smaller than with wage rigidities. We also show that the effectiveness of monetary policy is higher with the standard Calvo compared to the Heterogeneous wage setting model. Therefore,

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it turns out that heterogeneous wage setting behavior is decisive for both the effectiveness and costs of monetary policy. Two important papers recently studied the importance of wage flexibility for the conduct of monetary policy and macroeconomic performance: Galí (2013) studies a closed economy NK model and shows that the macroeconomic consequences of wage flexibility depend on the type of the monetary policy rule choice of the Central Bank. For the context of an open economy, Galí and Monacelli (2014) illustrate that an increase in wage flexibility could reduce macroeconomic welfare in economies under an exchange rate peg. We contribute to this policy debate by emphasizing that it is not only the level of aggregate labor market flexibility but also the distribution of wage setting behavior across the economy what matters for the macroeconomic policymaking.

7. CONCLUSIONS

Nominal rigidities in prices and wages have proven to be two useful mechanisms that allow NK DSGE models to replicate several stylized facts observed in the data. For instance, the presence of nominal rigidities increases the persistence of some key variables after a shock and besides it allows for non-neutrality of monetary policy in the short run. However, the way this friction is usually incorporated in the DSGE models—staggering price and wage setting following Calvo (1983)—is somehow arbitrary, restrictive, and in contradiction to empirical findings regarding the timing of price and wage adjustments across economic sectors and occupations.

In order to bypass these shortcomings, several alternatives have been considered. These include models where the rigidity in prices and wages is not time dependent as in Calvo (1983) or Taylor (1999), but it is state dependent as in Caplin and Leahy (1991) or setups where nominal rigidities are the consequence of informational frictions [Mankiw and Reis (2002)]. In addition, some authors have preferred a specification where the Calvo scheme is preserved but at the same time extended to include greater heterogeneity in price and wage setting by allowing, for example, for sectoral differences in firms and types of households.

This paper can be framed within this latter strand of research. Therefore, an otherwise standard NK DSGE model is considered, but it is assumed that four types of firms (sectors) and four types of households set their prices and wages according to four different rules. These rules are sticky prices, sticky information, full flexibility, and indexation to previous price or wage inflation. The linearized model was estimated using Bayesian techniques for the United States from 1955 to 2008 and was then compared to more restricted specifications. Subsequently, the models were utilized to investigate the business cycle implications of wage and price setting heterogeneity.

Our estimation results show that most firms and households face rigidities in prices and wages either in a time-dependent manner or as a consequence of informational frictions. At the same time, the share of households with flexibility

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in wages is four times greater than the corresponding share of firms with flexible prices indicating that heterogeneity is an important feature characterize households' wage setting behavior. The estimated model can produce impulse responses which are in line with the dynamics observed in actual data.

The impulse responses also reveal that allowing heterogeneity in wage rigidity amplifies the macroeconomic fluctuations resulting from a technology shock whereas they mitigate the macroeconomic fluctuations resulting from a monetary tightening. We also identify interesting qualitative business cycle dynamics generated by the heterogeneity in wage rigidity, such as price and wage inflation persistence, which standard models with only Calvo-type wage rigidity fail to achieve. Moreover, our results suggest that the standard approach of modeling prices and wages symmetrically is a very strong assumption whose effects are not trivial. Finally, we find that the model with heterogeneity in wage and price setting fits the data the best compared to the models where wages are allowed to be flexible and prices are set according to heterogeneous price setting rules as in Coibion and Gorodnichenko (2011).

Incorporating heterogeneity in prices and wages in an otherwise standard DSGE model allows for compelling qualitative and quantitative results that deserve further attention. One natural path to follow is related to the implementation of the specification proposed in this paper, but in a medium-scale DSGE model in which other nominal, real, and financial frictions are considered. Considering these additional frictions would help to isolate the implications of heterogeneity in prices and wages and facilitate the performance of data fitting across models. Another more substantial extension would be to make the heterogeneity in the price and wage setting behavior endogenous by, for example, linking it to financial constraints faced by firms and households. These extensions we leave to future research.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/S1365100518000949.

NOTES

1. There is a profusion of literature on DSGE models using the Calvo scheme for prices and wages, with Smets and Wouters (2007) being one of the most influential.

2. The same dynamic for price inflation could be obtained using a model with stronger microeconomics linkages given by quadratic cost of price adjustment, as in Rotemberg (1982).

3. An interesting paper by Sheedy (2010) shows that allowing for heterogeneity in price determination generates an intrinsic persistence in aggregate inflation without the need to appeal to backward-looking pricing rules. The author achieves this result by moving away from the traditional assumption of random selection of firms that can adjust their prices and, instead, by assuming that the hazard function for changes in prices has a positive slope. We are not aware of a similar implementation for the case of the determination of wages, but this could suggest an additional channel through which the heterogeneity in the setting of wages is relevant for business cycles and monetary policy.

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4. A non-exhaustive list of papers dealing with heterogeneity in price setting behavior includes: Alvarez et al. (2006), Angeloni et al. (2006), Aoki (2001), Bils and Klenow (2004), Carlsson and Skans (2012), Carvalho (2006), Dhyne et al. (2006), Goldberg and Hellerstein (2009), Hoeberichts and Stokman (2006), Klenow and Kryvtsov (2008), Middleditch (2010), Midrigan (2011), Nakamura and Steinsson (2008), and Vermeulen et al. (2012).

5. Bihan et al. (2012) findings indicate that wages are more rigid in the service sector, especially for managers, and in firms with 20–49 employees. The authors show that wages closer to the minimum wage are more likely to change in the third quarter.

6. Lünnemann and Wintr (2009) find that wage changes are more frequent for civil servants and white-collar workers.

7. Regarding industries, Sigurdsson and Sigurdardottir (2012) findings reveal that wages are more flexible in transport and trade—and relatively more rigid in financial services. Regarding occupations, the analysis points out to lower rigidity in sales and support positions and higher rigidity for the managerial level. With regard to firm size, bigger firms tend to change their wages more frequently than smaller firms.

8. Druant et al. (2012) find that the share of white-collar workers is positively associated with wage stickiness. The authors also show that the sectors that more clearly show a seasonal pattern in their wage adjustments are market and financial services, while construction is the sector with the least clear pattern.

9. An extended treatment can be found in Woodford (2003).

10. Some recent papers dealing with the importance of nominal wage rigidity include, for example, Carlstrom and Fuerst (2010), Campolmi (2014), and Belgibayeva and Horvath (2017).

11. The solution and estimation of the model was done using Dynare [Adjemian et al. (2011)]. The code is available upon request.

12. Market clearing in the goods market requires $Y_t = C_t$.

13. By construction, the number of past periods considered goes to infinity. The value chosen for J was determined for a technical reason related to the increasingly computational burden associated with higher values for J in the estimation process. As noted by Verona and Wolters (2014), in papers dealing with sticky information, the truncation point ranges from 3 to 252 periods.

14. In order to guarantee that the estimated values for the share of each sector are between 0 and 1 and add to 1, in the estimation step $\widehat{s}^p_{sp}$, $\widehat{s}^p_{si}$, and $\widehat{s}^p_{fl}$ were considered. Therefore, $s^p_{sp} = \widehat{s}^p_{sp}$, $s^p_{si} = \widehat{s}^p_{si}\left(1-\widehat{s}^p_{sp}\right)$, $s^p_{fl} = \widehat{s}^p_{fl}\left(\widehat{s}^p_{sp}-1\right)\left(\widehat{s}^p_{si}-1\right)$, and $s^p_{rot} = \left(1-\widehat{s}^p_{sp}\right)\left(\widehat{s}^p_{si}-1\right)\left(\widehat{s}^p_{fl}-1\right)$. In spite of this, the reported values presented below correspond to the shares in equation (9).

15. Bonds are riskless and have a one-period maturity, i.e., each bond bought at period t pays one unit of money at $t+1$. In the model bonds are in zero net supply. Taxes are set to zero because we did not model the government.

16. The remarks in footnote 14 also apply in this case.

17. The inclusion of wage inflation in the Taylor Rule is based on the notion that it is convenient that the Central Bank reacts to all the nominal rigidities observed in the economy, in the case of the paper at hand, rigidities in prices and in wages [Galí (2008)]. In this regard, Erceg et al. (2000) and Amato and Laubach (2003) found that it is desirable for the monetary policy, in the framework of simple interest rate rules, to respond to both price inflation and wage inflation.

18. A brief description of Bayesian Methods and their application in DSGE models can be found in Fernández-Villaverde (2010) and An and Schorfheide (2007). A textbook approach is available in Canova (2007) and DeJong and Dave (2011).

19. This choice is based on the lack of information on the share of each of the four ways of setting prices and wages. We choose an equal prior share for each price and wage setting behavior to allow the estimation of the shares to start from a level playing field.

20. Sargent (1989) and Karagedikli et al. (2010) discuss the importance of measurement error in improving the fit of DSGE models. Coibion and Gorodnichenko (2011) include measurement errors to absorb short-term fluctuations that are not modeled by the structural shocks.

21. Hirose and Inoue (2016) found that in linearized DSGE models that do not consider the zero-lower bound, the estimated parameters could be biased depending on the probability of hitting the

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zero-lower bound and the duration of its spell. As a robustness check we also estimated the model using the sample 1995:1 to 2014:1 finding no significant changes in the estimated parameters nor in the response of the variables to the shocks.

22. This detrending method avoids the introduction of spurious dynamic relations in the detrended variable (a well-known issue of other methods, e.g., the Hodrick-Prescott filter) and therefore "consistently estimates well-defined population characteristics for a broad class of possible data-generating processes" [Hamilton (2017)]. As proposed by Hamilton (2017), we also stationarized the variables using $y_t - \hat{\beta}_0 - \hat{\beta}_1 y_{t-8} - \hat{\beta}_2 y_{t-9} - \hat{\beta}_3 y_{t-10} - \hat{\beta}_4 y_{t-11}$, obtaining similar results. We opted for $v_{t+h} = y_{t+h} - y_t$ because it does not depend on future observations of y_t and thus it has the convenience of one-sided approaches.

23. We also estimate models using two chains with 500,000 replications each and an acceptance rate of about 1/3. The results are similar to those presented in this section. In addition, the univariate and multivariate convergence diagnosis of Brooks and Gelman shows convergence for the 80% interval, the second and the third moment of the distribution. The results are available upon request.

24. In comparison, Coibion and Gorodnichenko (2011) found an average duration for price contracts with informational frictions ranging from 4 to 20 quarters.

25. None of the estimated models are able to reproduce the hump shape in the response of output gap. This anomaly can be explained by taking into account that the models in the current paper are very stylized and do not take into account other rigidities, particularly consumption habits.

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