WAGE RIGIDITIES IN AN ESTIMATED DYNAMIC, STOCHASTIC, GENERAL EQUILIBRIUM MODEL OF THE UK LABOUR MARKET*

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We estimate a New Keynesian model with matching frictions and nominal wage rigidities on UK data. We show that in a model with matching frictions, whether nominal wage rigidities are relevant or irrelevant for inflation dynamics depends on the parametrization. At the estimated equilibrium, we find that wage rigidities are irrelevant, despite improving the empirical performance of the model. The reason is that with matching frictions, marginal costs depend on unit labour costs and on an additional component related to search costs. Wage rigidities affect both components in opposite ways leaving marginal costs and inflation virtually unaffected.

1 INTRODUCTION

Dynamic, stochastic, general equilibrium (DSGE) models based on the New Keynesian paradigm have become a powerful tool to investigate the propagation of shocks and inflation dynamics.[1] In this framework price rigidities establish a link between nominal and real activity: if nominal prices are staggered, fluctuations of nominal aggregates trigger fluctuations of real aggregates. Using this framework, seminal work by Gali and Gertler (1999)

has documented that the dynamic behaviour of inflation is tightly linked to firms' marginal cost (represented by unit labour cost), whose dynamics crucially depend on the functioning of the labour market.

Gali and Gertler (1999) assume frictionless labour markets, whereas we develop the analysis in a model based on labour market frictions. We believe that including labour market frictions is important for two reasons. First, they provide a comprehensive description of the labour market and enable us to introduce unemployment into the model. Importantly for the study in this paper, as shown in Krause and Lubik (2007), these frictions, once incorporated in a New Keynesian model, enrich the notion of marginal cost, by incorporating the costs of establishing a work relationship over and above the unit labour cost, thereby, in principle, altering the dynamics of inflation. Second, a growing number of empirical studies document that embedding labour market frictions into a standard New Keynesian model improves the model's empirical performance and enables a more accurate description of inflation dynamics.[2]

The contribution of our paper is twofold. First, we build on previous studies documented below to estimate a New Keynesian model characterized by labour market frictions using UK data. The estimation allows us to estimate the structural parameters of the UK economy, the unobservable shocks and study their transmission mechanism. Second, we investigate how staggered nominal wage negotiations affect the propagation of shocks and the ability of the model to fit the data. To this end, the theoretical framework allows, but does not require, nominal wage rigidities to affect the model's dynamics, therefore leaving the data to establish the importance of wage rigidities. In addition, this estimation strategy allows us to investigate the effect of nominal wage rigidities on inflation dynamics.

Our findings are the following. First, we estimate important structural parameters that characterize the British economy. In particular, we identify a relatively low Frisch elasticity of labour supply, reflecting the fact that employment is more volatile along the extensive margin than the intensive margin. The bargaining power of the workers is estimated to equal about 0.9. At the estimated equilibrium, firm's surplus is approximately 10 per cent relative to productivity, which is higher than the value of 2.5 per cent calibrated by Hagedorn and Manovskii (2008) to match the US data. The habit persistence parameter is close to zero, differently from the high value of approximately 0.6 in US data. We find that on average prices adjust every two quarters, in line with UK micro-estimates in Bunn and Ellis (2009), whereas the average frequency of wage negotiations is about three quarters. We also provide estimates for the monetary authority's reaction function. We find that the monetary authority's response to inflation and output is strong

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[2]Noticeable examples, documented below, are Gertler *et al.* (2008), Christoffel *et al.* (2009b), Krause *et al.* (2008b), Zanetti (2011) and Ravenna and Walsh (2008).

and there is a mild degree of interest rate inertia. The estimated model allows us to characterize the transmission of shocks. We investigate how the model variables react to supply and demand shocks, and we find that neutral and investment-specific technology shocks are more important than other shocks in explaining the data.

We establish that staggered wage setting enables the model to fit the data more closely. However, we find that at the estimated equilibrium wage rigidities are irrelevant for inflation dynamics. This result echoes the findings by Krause and Lubik (2007). In a frictional labour market inflation depends on unit labour costs and on an additional term which is related to labour market frictions, i.e. to the expected change in the search costs incurred in finding a match. Following a shock, wage rigidities have a direct effect on the unit labour cost. However, the contribution of unit labour costs to marginal costs is offset by the contribution of the component related to labour market frictions. For instance, following a positive mark-up shock, nominal wage rigidities attenuate the drop in unit labour costs and induce a fall in the frictional component of marginal costs compared with a flexible wage regime. As a result, marginal costs and inflation dynamics behave similarly in the two settings. A similar result holds for all the shocks in our model economy and stands in sharp contrast with those obtained in New Keynesian models with competitive labour markets. Absent search frictions in the labour market, the dynamics of inflation are only driven by the unit labour costs. It follows that wage rigidities generate inflation persistence by making unit labour costs more persistent (see Christiano *et al.*, 2005).

In this paper we also investigate whether the irrelevance of wage rigidities for inflation dynamics is built into the model, which potentially may prevent wage rigidities from affecting the dynamics of inflation, or it is a consequence of the specific estimation. To answer this question we simulate the theoretical framework by drawing 1000 times from the parameter posteriors and we compare the variance of inflation from the baseline model with wage rigidities and an otherwise identical model where wages are flexible. It clearly emerges that the variance of inflation in the model with flexible wages is greater than in the model with sticky wages for a wide range of parameter values. So we find that in our model the irrelevance result obtained by Krause and Lubik (2007) only holds for some particular calibrations. However, for the estimated parameters the variance of inflation is identical in the two models. This shows that the theoretical framework allows nominal wage rigidities to have relevant consequences for inflation dynamics, but the data prefer a version of the model in which wage rigidities are irrelevant for inflation dynamics. This result stands in contrast with those found by Gertler *et al.* (2008) in a similar analysis of the US labour market.

The paper is related to several studies. As in Krause and Lubik (2007), Krause *et al.* (2008a, 2008b), Ravenna and Walsh (2008), Zanetti (2011) and Christiano *et al.* (2011), we internalize the importance of labour market

frictions to describe inflation dynamics, but we also extend the framework to incorporate and test the empirical relevance of staggered wage setting. In this respect, our approach is similar to Gertler *et al.* (2008). However, our work differs from theirs as we allow firms to change the labour input along both the extensive and the intensive margin, and we simplify the modelling of wage rigidities following Thomas (2008). Moreover, by assuming that newly hired workers become immediately productive we introduce an instantaneous channel from wages to inflation without departing from efficient bargaining on hours. As shown by Trigari (2006), under efficient bargaining on hours and a delay in the timing of the matching function, there is no link between current period wages and marginal costs. The intuition is straightforward: if it takes time for workers to contribute to production, firms can change output only by changing hours. As a result, current period marginal costs will only depend on hours. But when hours are efficiently bargained the number of hours will depend only on the ratio between the marginal rate of substitution and the marginal product of labour, which in turn are independent of wages. In order to introduce a link between current period wages and marginal costs, a number of authors have abandoned the assumption of efficient bargaining to investigate the implications of right to manage (Christoffel and Linzert, 2006; Christoffel and Kuester, 2008; Mattesini and Rossi, 2008; Christoffel *et al.*, 2009a; Zanetti, 2011). We build on this literature by showing that a contemporaneous timing of the matching function restores a wage channel in the presence of efficient bargaining on hours. However, we find that at the estimated equilibrium the wage channel is unable to affect inflation dynamics. This paper is also related to the studies of Erceg *et al.* (2000) and Christiano *et al.* (2007) who investigate the effect of wage rigidities on the dynamics of New Keynesian models and inflation. We add to this line of research by extending the analysis to labour market frictions. Finally, differently from all the aforementioned studies, we are the first to estimate a model with labour market frictions and nominal wage rigidities on the UK economy.

The remainder of the paper is organized as follows. Section 2 sets up the model and details the specification of marginal costs. Section 3 presents the results of the estimation. Section 4 uses impulse response functions to lay out the transmission mechanism of the model. It then evaluates the importance of each shock in explaining the dynamics of the endogenous variables, and finally uses the reduced form of the model to recover the dynamics of the unobserved shocks. Section 5 investigates whether the irrelevance of wage rigidities for inflation dynamics is built into the theoretical framework. Finally, Section 6 concludes.

2 THE MODEL

The model combines the search and matching framework in Krause *et al.* (2008a) with the staggered wage-setting mechanism in Thomas (2008). The

economy consists of: households; firms, comprised of a continuum of producers indexed by $j \in [0, 1]$ and retailers; a monetary authority and a fiscal authority. In what follows we explain the structure of the labour market and the problems faced by households and firms. We conclude by detailing the specification of marginal costs.

2.1   The Labour Market

The matching of workers and firms is established by the standard matching function $M(U_t, V_t) = mU_t^{\xi}V_t^{1-\xi}$, which represents the aggregate flow of hires in a unit period.[3] The variable U_t denotes aggregate unemployment and V_t aggregate vacancies, $m > 0$ captures matching efficiency and $0 < \xi < 1$ denotes the elasticity of the matching function with respect to unemployment. During each period, vacancies are filled with probability $q(\theta_t) = M_t/V_t$, where $\theta_t = V_t/U_t$ denotes labour market tightness. Constant returns to scale in the matching function imply that workers find a job with probability $\theta_t q(\theta_t)$.

We assume that new hires start working at the beginning of each period t, and at the end of each period a constant fraction of workers loses the job with probability ρ.[4] Consequently, the evolution of aggregate employment N_t is[5]

$$N_t = (1-\rho)N_{t-1} + M_t \tag{1}$$

Workers who lose the job at time $t-1$ can look for a job at the beginning of time t. The stock of workers searching for a job at time t is therefore given by the number of workers who did not work in $t-1$, $1 - N_{t-1}$, plus those who lost their job at the end of the period, ρN_{t-1}. The evolution of aggregate unemployment can be written as $U_t = 1 - (1 - \rho)N_{t-1}$.

2.2   Households

The economy is populated by a unit measure of households whose members can be either employed or unemployed. We follow Merz (1995) and Andolfatto (1996) in assuming that members of the representative household perfectly insure each other against fluctuations in income. The problem of the representative household is to maximize an expected utility function of the form

$$E_t \sum_{s=0}^{\infty} \beta^s \zeta_{t+s} \left[\frac{(c_{t+s} - \varsigma C_{t+s-1})^{1-\sigma} - 1}{1-\sigma} - \chi_{t+s} \int_0^1 n_{jt+s} \frac{h_{jt+s}^{1+\mu}}{1+\mu} \, \mathrm{d}j \right] \tag{2}$$

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[3]Note that $U_t = \int_0^1 u_{jt}\mathrm{d}j$ and $V_t = \int_0^1 v_{jt}\mathrm{d}j$.
[4]The assumption that new hires contribute to employment during period t is supported by microeconomic evidence as in Davis *et al.* (2013) and references therein.
[5]Note that $N_t = \int_0^1 n_{jt}\mathrm{d}j$.

where β is the discount factor, ζ_t is a preference shock and χ_t is a labour supply shock. The variable c_t denotes consumption of the representative household at time t, while C_{t-1} denotes aggregate consumption in period $t-1$, and ς is an index of external consumption habits. The variable n_{jt} denotes the number of household members employed in firm j, and h_{jt} denotes the corresponding number of hours. The parameter σ governs the degree of risk aversion and μ is the inverse of the Frisch elasticity of labour supply. Consumption c_t is a Dixit–Stiglitz aggregator of a bundle of differentiated goods: $c_t = \left[\int_0^1 c_t(j)^{(\varepsilon_t-1)/\varepsilon_t} \, \mathrm{d}j \right]^{\varepsilon_t/(\varepsilon_t-1)}$, where ε_t is the stochastic elasticity of substitution among differentiated goods. Denoting by p_{jt} the price of a variety produced by a monopolistic competitor j, the expenditure minimizing price index associated with the representative consumption bundle c_t is: $p_t = \left[\int_0^1 p_t(j)^{1-\varepsilon_t} \, \mathrm{d}j \right]^{1/(1-\varepsilon_t)}$. The household faces the following budget constraint:

$$I_t + c_t + \frac{B_t}{p_t} = R_{t-1} \frac{B_{t-1}}{p_t} + \int_0^1 \frac{w_{jt}}{p_t} n_{jt} h_{jt} \mathrm{d}j + (1-n_t)b + r_t^k k_t + d_t + T_t \qquad (3)$$

which dictates that expenditure, on the left-hand side (LHS), must equal income, on the right-hand side (RHS). The households' expenditure is investment, I_t, consumption, c_t, and the acquisition of bonds, B_t/p_t. Households' income is the stock of bonds B_{t-1}/p_t from previous period $t-1$ which pay a gross nominal interest rate R_{t-1}, the proceeds from working in the firms indexed by j, $\int_0^1 (w_{jt}/p_t) n_{jt} h_{jt} \mathrm{d}j$,[6] and the unemployed benefits, b, earned by each unemployed member of the household. In addition, the household earns proceeds from renting capital, k_t, to the firms at the rate r_t^k, the real dividends from owning the firms, d_t, and the net government transfer T_t.

The household chooses c_t, B_t and k_{t+1} to maximize the utility function (2), subject to the budget constraint in equation (3) and the law of motion for capital,

$$k_{t+1} = \phi_t I_t + (1-\delta_k)k_t \qquad (4)$$

where δ_k denotes the rate of capital depreciation and ϕ_t denotes an investment-specific technology shock. By substituting equation (4) into (3), and letting λ_t denote the Lagrange multiplier on the budget constraint, the first-order conditions with respect to c_t, B_t and k_{t+1} are

$$\lambda_t = \zeta_t (c_t - \varsigma C_{t-1})^{-\sigma} \qquad (5)$$

$$\lambda_t = \beta E_t (\lambda_{t+1} R_t / \pi_{t+1}) \qquad (6)$$

and

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[6]Note that with this notation w_{jt}, n_{jt} and h_{jt} are the wage employment and hours of work at firm j at time t respectively.

$$\lambda_t = \beta E_t \lambda_{t+1} [r^k_{t+1} + (1-\delta_k)] \tag{7}$$

where $\pi_{t+1} = p_{t+1}/p_t$ denotes the gross inflation rate. Equation (5) states that the Lagrange multiplier equals the marginal utility of consumption. Equations (6) and (7), once equation (5) is substituted in, are the standard household's Euler equations that describe the consumption and capital decisions respectively.

To conclude the description of the household we need to define the marginal value of being employed and unemployed. The marginal value of employment at firm j, W^E_{jt}, is given by

$$W^E_{jt} = \lambda_t \frac{w_{jt}}{p_t} h_{jt} - \zeta_t \chi_t \frac{h^{1+\mu}_{jt}}{1+\mu} + \beta E_t \lambda_{t+1} [\rho W^U_{t+1} + (1-\rho) W^E_{jt+1}] \tag{8}$$

which states that the marginal value of a job for a worker is given by the real wage bill net of the disutility of work plus the expected-discounted value from being either employed or unemployed in the following period. The marginal value of unemployment, W^U_t, is

$$W^U_t = \lambda_t b + \beta E_t \lambda_{t+1} \{[1 - \theta_{t+1} q(\theta_{t+1})] W^U_{t+1} + (1-\rho)\theta_{t+1} q(\theta_{t+1}) \hat{W}^E_{t+1}\} \tag{9}$$

where $E_t \hat{W}^E_{t+1} = \int_0^1 W^E_{jt+1} dj$ is the expected value of employment in $t+1$. This equation states that the marginal value of unemployment is the sum of unemployment benefits plus the expected-discounted value from being either employed or unemployed in $t+1$. Using equations (8) and (9) we determine the household's net value of employment at firm j, $W^E_{jt} - W^U_t$, denoted by W_{jt}, as

$$W_{jt} = \lambda_t \frac{w_{jt}}{p_t} h_{jt} - \lambda_t b - \zeta_t \chi_t \frac{h^{1+\mu}_{jt}}{1+\mu} + \beta E_t \lambda_{t+1} (1-\rho) \left[W_{jt+1} - \theta_{t+1} q(\theta_{t+1}) \hat{W}_{t+1} \right] \tag{10}$$

where $E_t \hat{W}_{t+1} = \int_0^1 W_{jt+1} dj$.

2.3   Firms

We assume two types of firms: producers and retailers. Producers hire workers in a frictional labour market and rent capital in a perfectly competitive market. They manufacture a homogeneous intermediate good and sell it to retailers in a perfectly competitive market. Retailers transform intermediate inputs from the production sector into differentiated goods and sell them to consumers. As it is standard in the New Keynesian literature, we assume staggered price adjustment *à la* Calvo (1983). In what follows we describe the problems of the producers and retailers in detail.

2.3.1   Producers.   There is a continuum of producers of unit measure selling homogeneous goods at the competitive price φ_t. During each period t,

firm j manufactures y_{jt} units of goods according to the following production technology $y_{jt} = A_t (n_{jt} h_{jt})^\alpha k_{jt}^{1-\alpha}$, where A_t is a stochastic variable capturing neutral technology shocks. We assume constant returns to scale in production implying that all firms have the same capital–labour ratio $k_{jt}/n_{jt} h_{jt} = k_t/n_t h_t$ for all j. Consequently, the marginal product of labour is also equalized across firms such that $mpl_{jt} = mpl_t$.

Firms open vacancies at time t to choose employment in the same period; the cost of opening vacancies is $\mathcal{C}(v_{jt}) = a v_{jt}^{\varepsilon_c}$, where $a > 0$ is a scaling factor and $\varepsilon_c > 1$ is the elasticity of hiring costs with respect to vacancies. The vacancy cost function is assumed to be convex in order to produce an equilibrium where all the firms post vacancies. If the vacancy cost function were linear all firms would face the same marginal vacancy posting cost. Since we assume staggered nominal wage negotiations, it follows that only the firm with the lowest wage would hire at equilibrium. In our model wage dispersion implies that firms with high wages face low marginal return from search and low marginal vacancy posting costs since they hire only a relatively small number of workers.

The problem of the firm is to choose v_{jt}, n_{jt} and k_{jt+1} to maximize the present value of future discounted profits:

$$\max E_t \sum_{s=0}^{\infty} \beta^s \frac{\lambda_{t+s}}{\lambda_t} \left[\varphi_{t+s} y_{t+s} - \frac{w_{jt}}{p_t} n_{jt+s} h_{jt+s} - \mathcal{C}(v_{jt+s}) - k_{jt+s} r_{t+s}^k \right]$$

subject to the production function and the law of motion for employment:

$$n_{jt} = (1-\rho) n_{jt-1} + v_{jt} q(\theta_t) \qquad (11)$$

Since households own the firms, future profits are discounted at the rate $\beta^s \lambda_{t+s}/\lambda_t$. Letting J_{jt} denote the Lagrange multiplier on the employment constraint (11), the first-order conditions with respect to k_{jt+1}, v_{jt} and n_{jt} are

$$r_t^k = \varphi_t (1-\alpha) A_t (n_{jt} h_{jt})^\alpha k_{jt}^{-\alpha} \qquad (12)$$

$$\frac{\mathcal{C}'(v_{jt})}{q(\theta_t)} = J_{jt} \qquad (13)$$

$$J_{jt} = \varphi_t \alpha A_t (n_{jt} h_{jt})^{\alpha-1} k_{jt}^{1-\alpha} h_{jt} - \frac{w_{jt}}{p_t} h_{jt} + \beta(1-\rho) E_t \frac{\lambda_{t+1}}{\lambda_t} J_{jt+1} \qquad (14)$$

Equation (12) implies that returns to capital equalize the marginal revenue product. Equation (13) implies that the per period cost of filling a vacancy $\mathcal{C}'(v_{jt})$ times the average vacancy duration $1/q(\theta_t)$ must equal the shadow value of employment J_{jt}. Equation (14) shows that the shadow value of employment to the firm equals current period profits, i.e. the marginal revenue product of employment net of wage costs, plus the continuation value. Substituting equation (13) into equation (14) yields the standard job creation condition:

$$\frac{C'(v_{jt})}{q(\theta_t)} = \varphi_t \alpha A_t (n_{jt} h_{jt})^{\alpha-1} k_{jt}^{1-\alpha} h_{jt} - \frac{w_{jt}}{p_t} h_{jt} + \beta(1-\rho) E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{C'(v_{jt+1})}{q(\theta_{t+1})} \qquad (15)$$

which states that the cost of hiring an additional worker (LHS) equals the marginal benefit (RHS) that the additional worker brings into the firm.

2.3.2   Retailers.   There is a unit measure of retailers who transform homogeneous goods from the production sector into differentiated goods. Monopolistic competition implies that each retailer j faces the following demand for its own product

$$c_{jt} = \left(\frac{p_{jt}}{pt}\right)^{-\varepsilon_t} c_t \qquad (16)$$

where c_t is aggregate demand of the consumption bundle. Each retailer produces c_{jt} units of output using the same amount of inputs from the production sector. We assume price stickiness *à la* Calvo (1983), meaning that during each period a random fraction of firms, δ_p, are not allowed to reset their price.

The problem of the retailers is to choose p_{jt} to maximize

$$\max E_t \sum_{s=0}^{\infty} \delta_p^s \beta^s \frac{\lambda_{t+s}}{\lambda_t} \left(\frac{p_{jt}}{p_{t+s}} - \varphi_{t+s}\right) c_{jt+s}$$

subject to the demand function (16). The optimal pricing decision is

$$E_t \sum_{s=0}^{\infty} \delta_p^s \beta^s \frac{\lambda_{t+s}}{\lambda_t} \left(\frac{p_t^*}{p_{t+s}} - \frac{\varepsilon_t}{\varepsilon_t - 1} \varphi_{t+s}\right) = 0 \qquad (17)$$

where p_t^* is the optimal price chosen by all firms renegotiating at time t. This implies that forward-looking firms choose the optimal price such that the time-varying mark-up is equal to $\varepsilon_t/(\varepsilon_t - 1)$. Since firms are randomly selected to change price, the law of motion for the aggregate price level is

$$p_t^{1-\varepsilon_t} = \delta_p p_{t-1}^{1-\varepsilon_t} + (1-\delta_p)(p_t^*)^{1-\varepsilon_t} \qquad (18)$$

2.4   Wage Bargaining

Similarly to the price-setting decision, we assume staggered nominal wage negotiations, meaning that each period only a random fraction of firms, $1 - \delta_w$, is allowed to renegotiate on nominal wages. Following Thomas (2008) we assume that the wage set by the renegotiating firm j satisfies the following sharing rule:

$$\eta_t J_{jt}^* = (1-\eta_t)\frac{W_{jt}^*}{\lambda_t} \qquad (19)$$

where $\eta_t \equiv \eta \varepsilon_t^{\eta}$ is the stochastic bargaining power of the workers and the superscript * denotes renegotiating workers and firms. This sharing rule implies that renegotiating workers obtain a fraction of the total surplus equal to their bargaining power.

Notice that this is different from Nash bargaining. With Nash bargaining wages maximize a weighted average of the joint surplus. Nash bargaining delivers the sharing rule, equation (19), only if wages are continuously renegotiated. As shown by Gertler and Trigari (2009), Nash bargaining implies that, in the presence of staggered nominal wage negotiations, the share parameter η_t in equation (19) would fluctuate over the cycle even if it were not subject to shocks. This follows from the fact that workers and firms face different time horizons when they consider the effects of different wages. However, Gertler and Trigari (2009) suggest that this 'horizon effect' has quantitatively negligible implications. We therefore choose to follow Thomas (2008) and adopt the sharing rule in equation (19) as it simplifies the analysis considerably.

With staggered wage negotiations, the shadow value of employment at firm j to the household that is allowed to renegotiate can be rewritten from equation (10) as follows:

$$\frac{W_{jt}^*}{\lambda_t} = \frac{w_{jt}^*}{p_t}h_{jt} - \tilde{w}_{jt} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1-\rho)\left[\delta_{\mathrm{w}}\frac{W_{jt+1|t}}{\lambda_{t+1}} - (1-\delta_{\mathrm{w}})\frac{W_{jt+1}^*}{\lambda_{t+1}}\right] \quad (20)$$

where the worker's opportunity cost of holding the job, $\tilde{w}_{jt}$, is equal to

$$\tilde{w}_{jt} = b + \frac{\zeta_t \chi_t}{\lambda_t}\frac{h_{jt}^{1+\mu}}{1+\mu} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1-\rho)\theta_{t+1}q(\theta_{t+1})\frac{\hat{W}_{t+1}}{\lambda_t}$$

The net value of employment to the household conditional on wage renegotiation at time t (equation (20)), equals the net flow income from employment, $(w_{jt}^*/p_t)h_{jt} - \tilde{w}_{jt}$, plus the continuation value, which is the last term on the RHS. The latter is equal to the sum of the marginal discounted value of employment in $t + 1$ conditional on the wage set at time t, if the firm does not renegotiate with probability δ_{w}, and the value of employment in $t + 1$ conditional on a renegotiation, with probability $1 - \delta_{\mathrm{w}}$. Similarly, the shadow value of employment to the renegotiating firm j can be written

$$J_{jt}^* = \bar{w}_{jt} - \frac{w_{jt}^*}{p_t}h_{jt} + (1-\rho)E_t \frac{\lambda_{t+1}}{\lambda_t}[\delta_{\mathrm{w}}J_{jt+1|t} + (1-\delta_{\mathrm{w}})J_{jt+1}^*] \quad (21)$$

where $\bar{w}_{jt} = \varphi_t mpl_t h_{jt}$ denotes the marginal revenue product. The marginal value of employment for a renegotiating firm equals the net flow value of the match plus the continuation value. In turn, this equals the marginal value of

employment in $t + 1$ conditional on the previous period wage, with probability δ_w, and the marginal value conditional on a wage renegotiation, with probability $1 - \delta_w$.

Iterating equations (20) and (21) forward and using the sharing rule in equation (19), it yields

$$E_t \sum_{s=0}^{\infty} \beta^s \frac{\lambda_{t+s}}{\lambda_t} (1-\rho)^s \delta_w^s \left(\frac{w_{jt}^*}{p_{t+s}} h_{jt+s} - w_{t+s}^{\text{tar}} \right) = 0 \qquad (22)$$

where $w_{jt+s}^{\text{tar}} = \eta_{t+s} \bar{w}_{jt+s} + (1-\eta_{t+s}) \tilde{w}_{jt+s}$ is the total real wage payment to the worker on which both parties would agree if wages were fully flexible. Substituting for $\bar{w}_{jt+s}$ and $\tilde{w}_{jt+s}$ the target real wage bill can be written

$$w_{jt+s}^{\text{tar}} = \eta_t \varphi_t mpl_t h_{jt} + (1-\eta_t) \left[b + \frac{\zeta_t \chi_t}{\lambda_t} \frac{h_{jt}^{1+\mu}}{1+\mu} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} (1-\rho) \theta_{t+1} q(\theta_{t+1}) \frac{\hat{W}_{t+1}}{\lambda_t} \right] \qquad (23)$$

Equation (23) is standard in the search and matching literature. The target real wage bill is expressed as a weighted average between the marginal revenue product of the worker and the opportunity cost of holding a job at the level of hours worked h_{jt}. Given that renegotiating firms are randomly chosen, the law of motion for the aggregate nominal wage is given by

$$w_t = \delta_w w_{t-1} + (1-\delta_w) w_t^* \qquad (24)$$

where $w_t = \int_0^1 w_{jt} \, dj$.

2.5   Hours Bargaining

We assume that hours and wages are bargained simultaneously and that bargaining on hours is efficient. Hence, hours satisfy the Nash bargaining criterion:

$$h_{jt} = \arg\max \left(\frac{W_{jt}^*}{\lambda_t} \right)^{\eta_t} (J_{jt}^*)^{1-\eta_t}$$

Using the sharing rule (19), the first-order condition becomes

$$\frac{\chi_t \zeta_t}{\lambda_t} h_{jt}^\mu = \varphi_t A_t \alpha^2 n_{jt}^{\alpha-1} h_{jt}^{\alpha-1} k_{jt}^{1-\alpha}$$

This equation states that the marginal rate of substitution, on the LHS, equals the marginal product of hours, on the RHS. Since the marginal return to the labour input is equalized across firms at equilibrium, it follows that

members of the household employed in different firms work the same amount of hours, i.e. $h_{jt} = h_t$. Solving the first-order condition for hours yields

$$h_{jt} = \eta_t \left(\frac{\varphi_t A_t \alpha^2 n_{jt}^{\alpha-1} k_{jt}^{1-\alpha}}{\chi_t \zeta_t} \lambda_t \right)^{\frac{1}{1+\mu-\alpha}} \tag{25}$$

2.6 Price and Wage Inflation

Following Calvo (1983), using equations (17) and (18) we derive the standard New Keynesian Phillips Curve:

$$\pi_t = k_{\mathrm{p}}(\hat{\varphi}_t + \varepsilon_t) + \beta E_t \pi_{t+1} \tag{26}$$

where a hat superscript denotes the variable's deviation from its steady state, and the coefficient k_{p} is equal to: $k_{\mathrm{p}} = [(1 - \beta\delta_{\mathrm{p}})(1 - \delta_{\mathrm{p}})]/\delta_{\mathrm{p}}$. Similarly, following Thomas (2008), using equations (22) and (24) we obtain the following equation for wage inflation:

$$\pi_{\mathrm{w}t} = k_{\mathrm{w}} \left[\hat{w}_t^{\mathrm{tar}} - \left(\hat{w}_t + \hat{h}_t \right) \right] + \beta (1 - \rho) E_t \pi_{\mathrm{w}t+1} \tag{27}$$

where $\hat{w}$ denotes the real wage and the coefficient k_{w} is equal to: $k_{\mathrm{w}} \equiv \{[(1 - \beta(1 - \rho)\delta_{\mathrm{w}}] (1 - \delta_{\mathrm{w}})\}/\delta_{\mathrm{w}}$.

Equation (27) states that the real wage inflation depends on the gap between the actual and target real wage bill, $\hat{w}_t + \hat{h}_t$ and $\hat{w}_t^{\mathrm{tar}}$ respectively. Inflation materializes whenever the real wage bill is below target, i.e. whenever the wage bill is below the level that would prevail if wages were perfectly flexible.

2.7 Closing the Model

The monetary authority sets the nominal interest rate following the Taylor rule: $(R_t/R^*) = (R_{t-1}/R^*)^{\rho_r} \left[(\pi_t/\pi^*)^{r_\pi} (y_t/y^*)^{r_y} \right]^{1-\rho_r} \varepsilon_t^R$, where an asterisk superscript denotes the steady-state values of the associated variables. The parameter ρ_r represents interest rate smoothing, and r_y and r_π govern the response of the monetary authority to deviations of output and inflation from their steady-state value. The error term ε_t^R denotes an independent and identically distributed (i.i.d.) monetary policy shock.

The fiscal authority is assumed to run a balanced budget: $B_t/p_t = R_{t-1}(B_{t-1}/p_t) + T_t + b(1 - n_t)$.

2.8 Marginal Costs

In this section we compare the specification of marginal costs in our model against alternative formulations in the literature. This is important to unveil some key properties of the model and understand the findings detailed in the next section. In a matching model with efficient bargaining on hours, Trigari

(2006) shows that whenever firms post vacancies at time t to control employment in the following period, the real marginal cost at time t is independent of wages at time t. The independence of current period marginal costs from current period real wages is typically referred to, in the literature, as the lack of a 'wage channel'. The intuition is straightforward. Since current hires contribute to next period employment, in the current period t firms can change production only by adjusting hours. This implies that the marginal cost of production at time t depends solely on hours. With efficient bargaining the number of hours worked is determined by the marginal rate of substitution between consumption and leisure and the marginal product of labour, and therefore it is independent of wages in the current period t. It follows that current wages are irrelevant for current period marginal costs.

Following Trigari (2006), a number of authors such as Christoffel and Kuester (2008), Christoffel and Linzert (2006) and Zanetti (2007) have restored the transmission channel from wages to prices by resorting to alternative bargaining schemes such as the right to manage. In our model we are able to restore a wage channel at time t while preserving efficient Nash bargaining. We do so by changing the timing assumption of the matching function. That is, we allow firms to control employment at time t by choosing vacancies in the same period, as described by equation (11). Under this timing assumption, the cost of increasing production at the margin depends on the cost of hiring an additional worker, which is represented by the wage paid to the new hire. This can be seen by solving the job creation condition in equation (14) for marginal costs φ_t:

$$\varphi_t = \frac{w_t}{p_t}\frac{h_t}{mpe_t} + \frac{J_t - \beta E_t \dfrac{\lambda_{t+1}}{\lambda_t}(1-\rho)J_{t+1}}{mpe_t} \tag{28}$$

where $mpe_t = A_t\alpha(n_{jt}h_{jt})^{\alpha-1}k_{jt}^{1-\alpha}h_{jt}$ denotes the marginal product of employment. From equation (28), as shown by Krause and Lubik (2007), real marginal costs are equal to the sum of the unit labour cost and an additional term related to matching frictions. Given that the shadow value of employment J_t equals the expected hiring cost, the second term on the RHS of equation (28) can be interpreted as the expected change in search costs. By equation (13), this term depends on the expected value of labour market tightness in the next period relative to the current period. Had we assumed that newly hired workers were unable to contribute to production immediately, the decision on vacancies would only affect next period marginal costs, leaving current period marginal costs solely dependent on the number of hours, which, due to efficient wage bargaining, are independent of wages.[7]

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[7]Note that in this instance future period marginal costs include wages. However, since future periods are discounted, the dynamics of future wages have a more limited effect on inflation.

3 ESTIMATION

The model is estimated with Bayesian methods. It is first loglinearized around the deterministic steady state. We then solve the model and apply the Kalman filter to evaluate the likelihood function of the observable variables. The likelihood function and the prior distribution of the parameters are combined to obtain the posterior distributions. The posterior kernel is simulated numerically using the Metropolis-Hasting algorithm.[8] We first discuss the data and the priors used in the estimation and then report the parameter estimates.

3.1 Priors and Data

The model is estimated over the period 1971:Q1–2009:Q4 using seven shocks and seven quarterly data series: consumption, investment, inflation, average hours, employment, the real wage and the nominal interest rate.[9] The data series are from the Office for National Statistics data set; the acronyms are indicated in italics. For consumption, we use data on 'household final consumption expenditure' (*ABJR*) and for investment we use data on 'business investment' (*NPEL*). We define 'output' to be the sum of these two series and the price level to be the implicit deflator associated with this measure of output ((*NPEK* + *ABJQ*)/(*NPEL* + *ABJR*)). Our employment series comes from the Labour Force Survey (*MGRZ*) and our series for average hours is calculated as 'total actual weekly hours worked' (*YBUS*) divided by 'employment'. We define the nominal wage as 'wages and salaries' (*ROYJ*) divided by 'total actual weekly hours worked'. The real wage is then this series divided by our series for the price level. The labour market variables, employment, hours and real wages, refer to the whole economy and are interpreted as proxies for the behaviour of the respective private sector variables since our model abstracts from the public sector. Finally, our nominal interest rate series is the 'London clearing banks' base rate (*AMIH*). The series for consumption, investment, average hours, employment and real wages are logged and then all series are passed through a Hodrick–Prescott filter with smoothing parameter 1600.

The seven shocks in the model are a preference shock, a mark-up shock, a labour supply shock, a neutral technology shock, a bargaining power shock, an investment-specific technology shock and a monetary policy shock.

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[8]We use two blocks of 250,000 draws. The sequence of draws is stable, providing evidence on convergence. An appendix that details evidence on convergence is available upon request from the authors.

[9]This sample period was characterized by multiple monetary policy regimes and changes in labour market institution. To enable the estimation to account for the influence of these breaks on the parameter estimates, an alternative estimation strategy would be to extend the estimation of the DSGE model with one regime shift proposed by Curdia and Finocchiaro (2013) to multiple regime changes. We leave this extension open to future research.

TABLE 1
FIXED PARAMETERS

Parameters	Description	Values
β	Discount factor	0.99
α	Labour share	0.69
δ_k	Capital depreciation rate	0.025
ε_c	Elasticity of the vacancy cost function	1.1
b	Unemployment benefits	0.58
ξ	Matching function elasticity	0.7
m	Constant matching function	0.6
ρ	Job destruction rate	0.03
ε	Elasticity of demand	11

All shocks, with the exception of monetary policy shock, are assumed to follow a first-order autoregressive process with i.i.d. normal error terms such that $\ln \kappa_{t+1} = \rho_\kappa \ln \kappa_t + v_t$, where the shock $\kappa \in \{\zeta, \chi, \varepsilon, A, \phi, \varepsilon^n\}$, $0 < \rho_\kappa < 1$ and $v_t \sim N(0, \sigma_\kappa)$. Monetary policy shocks ε_t^R are i.i.d.

The model contains 19 structural parameters, excluding the shock parameters. Before estimating the model we calibrate some parameters to match important long-run properties of the data. This is particularly important for the parameters related to the labour market, since the information on labour market dynamics is limited in the data set and therefore the estimation is unable to deliver estimates that capture the long-run properties in the data. We start by discussing the fixed parameters, whose values are summarized in Table 1. The discount factor β is set at 0.99 implying a real interest rate of 4 per cent. The labour share parameter α is set equal to 0.69 in order to match the observed labour share over the period of the estimation and the capital depreciation parameter δ_k is set at 0.025 to match an average annual rate of capital destruction of 10 per cent. The elasticity of the vacancy cost function, ε_c, is also fixed. This parameter is set at 1.1, a value which is relatively close to the standard assumption of linear adjustment costs, and satisfies the assumption of convexity. The unemployment benefits coefficient, b, is calibrated to match a replacement ratio of 0.58, as in OECD (2007). This parameter is important to generate amplification of labour market variables. As shown by Hagedorn and Manovskii (2008), values of b close to unity generate responses of unemployment and vacancies to productivity shocks that are close to the data. When b is high, the value of a job to the worker is very close to the value of unemployment. In such instance the surplus of a job is very small and tiny changes in the productivity of the labour input produce a high percentage change in the total surplus of a match, boosting the response of employment. The elasticity of the matching function, ξ, is set to 0.7, as estimated by Petrongolo and Pissarides (2001) for the UK economy. The constant of the matching function, m, is set equal to 0.5 to match the job-finding rate of 35 per cent, in line with evidence from the Labour Force

	Description	Prior distribution			Posterior distribution		
			5%	*95%*	*Mean*	*5%*	*95%*
σ	Relative risk aversion	*Gamma* (0.66, 0.2)	0.37	1.03	0.73	0.60	0.86
ς	Habit persistence	*Beta* (0.5, 0.2)	0.17	0.83	0.04	0.01	0.07
μ	Inverse Frisch elasticity	*Gamma* (1, 0.1)	0.84	1.17	1.64	1.51	1.77
a	Const. vacancy cost function	*Gamma* (2.5, 1)	1.10	4.32	1.88	0.8	3.2
η	Workers' bargaining power	*Beta* (0.5, 0.2)	0.17	0.83	0.87	0.84	0.90
δ_w	Calvo wage parameter	*Beta* (0.5, 0.25)	0.10	0.90	0.63	0.37	0.90
δ_p	Calvo price parameter	*Beta* (0.5, 0.25)	0.10	0.90	0.52	0.20	0.80
r_π	Taylor rule response to inflation	*Gamma* (1.5, 0.05)	1.42	1.58	1.48	1.41	1.51
r_y	Taylor rule response to output	*Gamma* (0.125, 0.05)	0.06	0.22	0.31	0.27	0.35
ρ_r	Taylor rule inertia	*Beta* (0.5, 0.2)	0.17	0.83	0.53	0.50	0.55

Notes: The table reports the prior and posterior distribution of the estimated structural parameters together with 5 per cent and 95 per cent confidence intervals. The numbers in parenthesis are the mean and standard deviation of the distribution.

Survey. The job destruction rate, ρ, is set to 0.03, as estimated by Bell and Smith (2002) using Labour Force Survey data. Finally, the elasticity of demand, ε, is set to 11, a value suggested in Britton *et al.* (2000), which implies a steady-state mark-up of 10 per cent. Finally, the steady-state gross inflation rate, π, is set equal to 1.

The remaining parameters are estimated. We use the beta distribution for parameters that take sensible values between zero and one, the gamma distribution for coefficients restricted to be positive and the inverse gamma distribution for the shock variances. Tables 2 and 3 report priors, posterior estimates and 90 per cent confidence intervals for the structural and shock parameters respectively.

The prior mean of the relative risk aversion, σ, is set equal to 0.66. The prior mean of the index of external habit, ς, is set at its middle value of 0.5, as in Gertler *et al.* (2008). The prior mean of the inverse of the Frisch elasticity of labour supply, μ, is set equal to 1, as in Krause *et al.* (2008a). The prior mean of the scaling factor of the cost of posting a vacancy, a, is set equal to 3 such that the cost of posting a vacancy is approximately 1 per cent of total output at the steady state, as in Blanchard and Gali (2010). The prior mean of the worker bargaining power, η, is set to 0.5, such that the firm and the worker they equally split the surplus from working.

The prior mean of the Calvo parameter on prices, δ_p, is set to 0.5 in order to match an average duration of prices of about six months, in line with the evidence in Bunn and Ellis (2009) for the UK economy. We take an agnostic view on whether wages are more flexible than prices, and therefore set the prior mean of the Calvo parameter on wages, δ_w, to 0.5.

We choose the prior means of the Taylor rule response to inflation, r_π, output, r_y, and the interest rate smoothing parameter, ρ_r, equal to 1.5, 0.125 and 0.5 respectively. These values are commonly used in the literature.

TABLE 3
PRIOR AND POSTERIOR DISTRIBUTION OF SHOCK PARAMETERS

Description		Prior distribution 5%	Prior distribution 95%	Posterior distribution Mean	Posterior distribution 5%	Posterior distribution 95%
Autoregressive parameters						
ρ_χ Labour supply	Beta (0.8, 0.2)	0.37	0.99	0.84	0.79	0.88
ρ_ζ Preferences	Beta (0.8, 0.2)	0.37	0.99	0.88	0.82	0.93
ρ_ε Mark-up	Beta (0.8, 0.2)	0.37	0.99	0.36	0.29	0.42
ρ_a Technology	Beta (0.8, 0.2)	0.37	0.99	0.24	0.17	0.31
ρ_i Investment	Beta (0.8, 0.2)	0.37	0.99	0.44	0.24	0.62
ρ_η Bargaining	Beta (0.8, 0.2)	0.37	0.99	0.16	0.07	0.26
Standard errors						
σ_χ Labour supply	IGamma (0.002, 0.3)	0.0004	0.0058	0.020	0.017	0.022
σ_ζ Preferences	IGamma (0.002, 0.3)	0.0004	0.0058	0.008	0.007	0.010
σ_ε Mark-up	IGamma (0.002, 0.3)	0.0004	0.0058	0.008	0.007	0.009
σ_a Technology	IGamma (0.002, 0.3)	0.0004	0.0058	0.018	0.016	0.020
σ_ε Monetary policy	IGamma (0.002, 0.3)	0.0004	0.0058	0.06	0.005	0.007
σ_i Investment	IGamma (0.002, 0.3)	0.0004	0.0058	0.190	0.130	0.250
σ_η Bargaining	IGamma (0.002, 0.3)	0.0004	0.0058	0.293	0.254	0.334

Notes: The table reports the prior and posterior distribution of the estimated structural parameters together with 5 per cent and 95 per cent confidence intervals. The numbers in parenthesis are the mean and standard deviation of the distribution.

Finally, Table 3 reports the prior distributions of the shock parameters. The prior mean of the autoregressive parameters is set equal to 0.8 and the prior mean of the standard errors is set equal to 0.002 for all the shocks. For the prior mean of the autoregressive parameters we choose values that are in between those selected by Gertler *et al.* (2008) and Krause *et al.* (2008a).

3.2   Parameter Estimates

The third, fourth and fifth columns of Table 2 show the posterior means of the structural parameters together with their 90 per cent confidence intervals. The posterior mean of the relative risk aversion σ is equal to 0.73, in the range of estimates in Brown and Gibbons (1985) for the USA. The posterior mean of the index of external habits ς is equal to 0.04, which is substantially lower than the estimate of 0.57 in Smets and Wouters (2003), therefore ruling out habit in consumption as an important source to generate persistence in the model.[10] The posterior mean of the inverse of the Frisch elasticity of labour supply μ is equal to 1.6, which is substantially higher than its prior, and in line with microeconomic estimates as surveyed by Card (1994). This high estimate reflects the fact that employment volatility is higher at the extensive margin than at the intensive margin. Krause *et al.* (2008a) obtain similar results for the USA, although their estimate is higher than ours.

The posterior mean of the constant of the vacancy cost function a is equal to 1.88, lower than its prior, which indicates that the model prefers a low cost of posting a vacancy, which is equal to 0.3 per cent of total output at the estimated equilibrium, similarly to the estimates in Silva and Toledo (2009) of approximately 0.2 per cent on US data. The posterior mean of the bargaining power of the workers η is equal to 0.87, thereby indicating that wages are closer to the marginal product of labour. This estimate is remarkably close to the value of 0.90 in Gertler *et al.* (2008) based on US data. Note that the value of η and b determine the equilibrium firm's surplus that is a key variable for the response of labour market variables to shocks, as shown in Hagedorn and Manovskii (2008). In particular, a low firm's surplus increases the response of labour market variables. The posterior means of the model implies a firm's surplus of approximately 10 per cent relative to productivity, which is higher than the value of 2.5 per cent in Hagedorn and Manovskii

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[10]The result that the estimated habit parameter takes a value close to zero is the same as found by Krause *et al.* (2008a) on US data. Their model does not have to rely on this source of intrinsic persistence to explain the behaviour of inflation and consumption because the estimated shocks are strongly autocorrelated. The UK inflation exhibits very low autocorrelation in the full sample, and zero autocorrelation from the mid-1980s onward. So our model does not have to rely on any source of persistence to explain inflation. The persistence of the UK consumption series is instead explained in our model by the persistence of the preference shocks, which explains 85 per cent of the variance of consumption on impact.

<div align="center">

TABLE 4
MARGINAL LOG-LIKELIHOOD FUNCTION

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Sticky wages	3466
Flexible wages	2944

(2008).[11] The unemployment rate is about 10 per cent at the estimated equilibrium, slightly higher than the average value of 7 per cent observed in the data, possibly accounting for the existence of workers who are only marginally attached to the labour force, and as such do not qualify as unemployed according to the International Labour Organization (ILO) definition. This higher unemployment rate implies that the job finding rate, around 28 per cent, is somewhat lower than our calibration target based on Labour Force Survey data.

The posterior means of the Calvo parameters on the frequency of wage and price negotiations, δ_w and δ_p, are equal to 0.63 and 0.52 respectively, showing that prices adjust more frequently than wages. These values imply an average frequency of wage negotiations of three quarters, in line with Dickens *et al.* (2007), and an average frequency of price negotiations of two quarters, in line with Bunn and Ellis (2009) for the UK economy. However, although the model prefers higher wage rigidities than price rigidities, the estimation shows a sizable uncertainty around its posterior mean.

Finally, the estimates of the Taylor rule parameters are as follows. The posterior means of the interest rate response to inflation and output, r_π and r_y, equal to 1.48 and 0.31, respectively, indicate a strong response to inflation and output. The posterior mean of the degree of interest rate smoothing, ρ_r, equal to 0.53 suggests a mild degree of interest rate inertia.

The third, fourth and fifth columns of Table 3 show the posterior means of the shock parameters together with their 90 per cent confidence intervals. The posterior means of the persistence parameters ρ_χ and ρ_ζ, equal to 0.84 and 0.88 respectively, indicate that shocks to the labour supply and preferences are substantially more persistent than the other shocks, which is in line with the estimates in Castelnuovo (2007) based on Euro Area data. The posterior means of the shocks' variance is close to 1 per cent for all the shocks, with the exception of investment-specific technology shocks, σ_i, and bargaining shocks, σ_η, which are more volatile.

In order to establish whether staggered wages are important to match the data, Table 4 reports the value of the marginal log-likelihood function for the estimated models with sticky and flexible wages respectively. Since the value of the marginal log-likelihood function associated with the model with

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[11]Note that when we estimated the model including time series for vacancies, the firm's surplus was similar to Hagedorn and Manovskii (2008), although the overall fit of the model was worse.

sticky wages is equal to 3466, and substantially higher than the value of 2944 associated with the flexible wage model, staggered wage setting enables the model to fit the data more closely, thereby suggesting that wages rigidities are important to replicate UK data.

4 IMPULSE RESPONSE FUNCTIONS AND VARIANCE DECOMPOSITION

In this section we investigate, by use of impulse responses, how the shocks are transmitted to the endogenous variables. In order to disentangle the effect of nominal wage rigidities we use our baseline model and an otherwise identical model where the Calvo parameter on wages is set to zero ($\delta_w = 0$).

Figures 1–5 plot the impulse responses of selected variables to a one standard deviation shock. Each entry compares the responses of the model with sticky wages (solid line) against those with flexible wages (dotted line).[12] Figure 1 shows that a one standard deviation mark-up shock leads to an increase in inflation. In turn, the resulting increase in the interest rate decreases consumption and investment. In reaction to the shock, the firm reduces the labour input along both the intensive and the extensive margin to decrease production. The qualitative responses of the variables in the staggered wage model are similar to those in the model with flexible wage setting, since mark-up shocks do not induce the firm to adjust labour market variables differently.

However, it is worth noting that wage rigidities affect the behaviour of nominal and real wages considerably, but the reaction of marginal costs and inflation remains remarkably similar in the two settings. Why are the inflation dynamics so similar? As detailed in Section 2.8, search frictions introduce an additional term into marginal costs, over and above unit labour costs, which reflects the expected change in search costs. Following a positive mark-up shock, nominal wage rigidities attenuate the drop in unit labour costs and induce a fall in the frictional component of marginal costs compared with a flexible wage regime. As a result, marginal costs and inflation dynamics behave similarly in the two settings. Wage rigidities attenuate the reaction of unit labour costs as firms are not allowed to renegotiate lower wages. At the same time, wage rigidities induce labour market tightness to fall on impact and then steadily increase. As a result, the firm's cost of searching for a worker falls on impact and it then rises over time.[13] The rising profile in expected search costs implies that the firm can save on future hiring costs by increasing current period hiring. From equation (28), higher expected search costs next period, translate in lower marginal costs in the current period. As

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[12]We show impulse responses for shocks to the mark-up, neutral technology, monetary policy, preferences and investment-specific technology. An appendix that details the impulse responses of the variables to all the shocks in the model is available upon request to the authors.

[13]Note that the average duration of a vacancy, $1/q(\theta_t)$, depends only on labour market tightness.
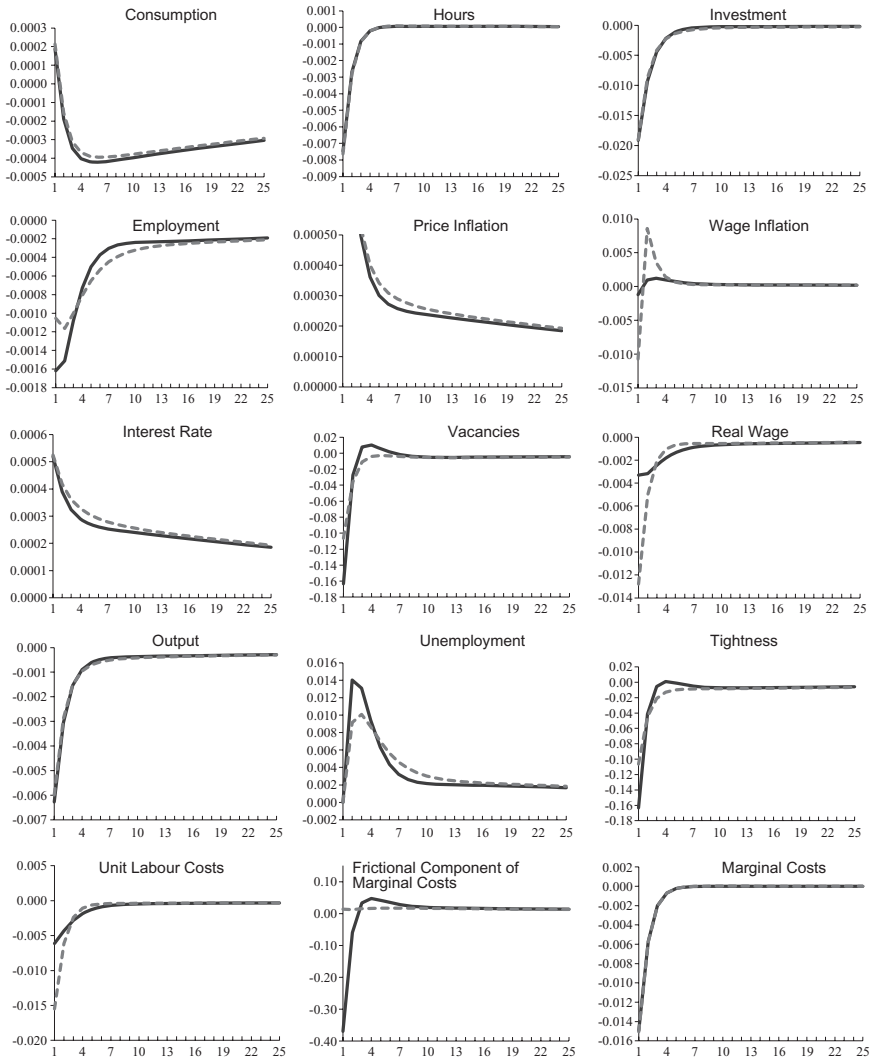
Fig. 1. Impulse Responses to a Mark-up Shock
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages. Impulse responses are expressed in percentage deviations from the steady state.
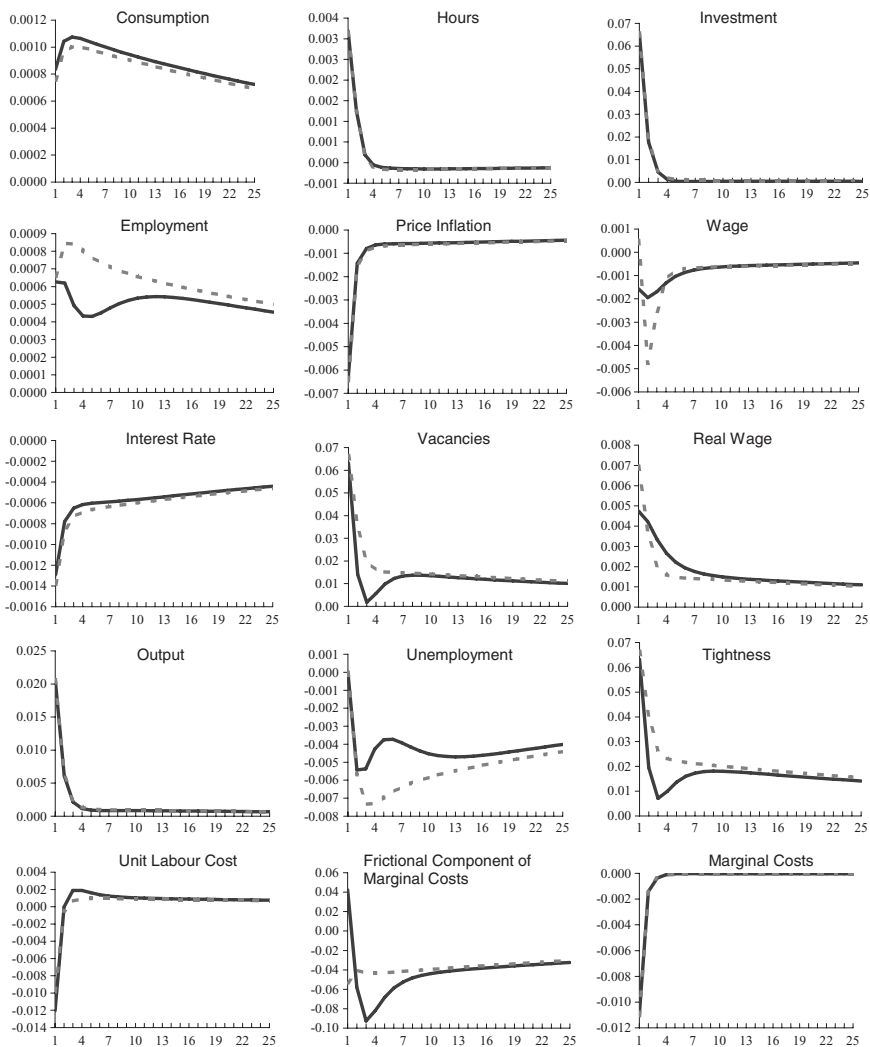
FIG. 2. Impulse Responses to a Neutral Technology Shock
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages. Impulse responses are expressed in percentage deviations from the steady state.

FIG. 3. Impulse Responses to a Monetary Policy Shock
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages. Impulse responses are expressed in percentage deviations from the steady state.
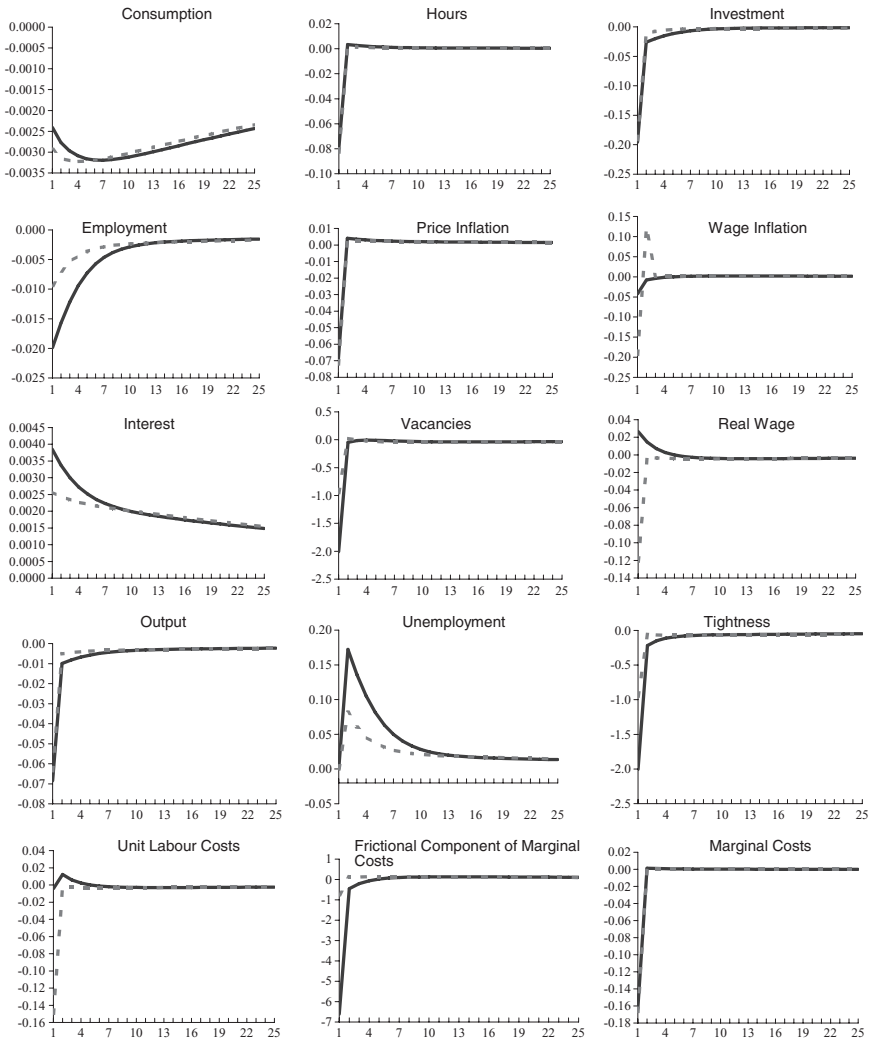
FIG. 4. Impulse Responses to a Preference Shock
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages. Impulse responses are expressed in percentage deviations from the steady state.
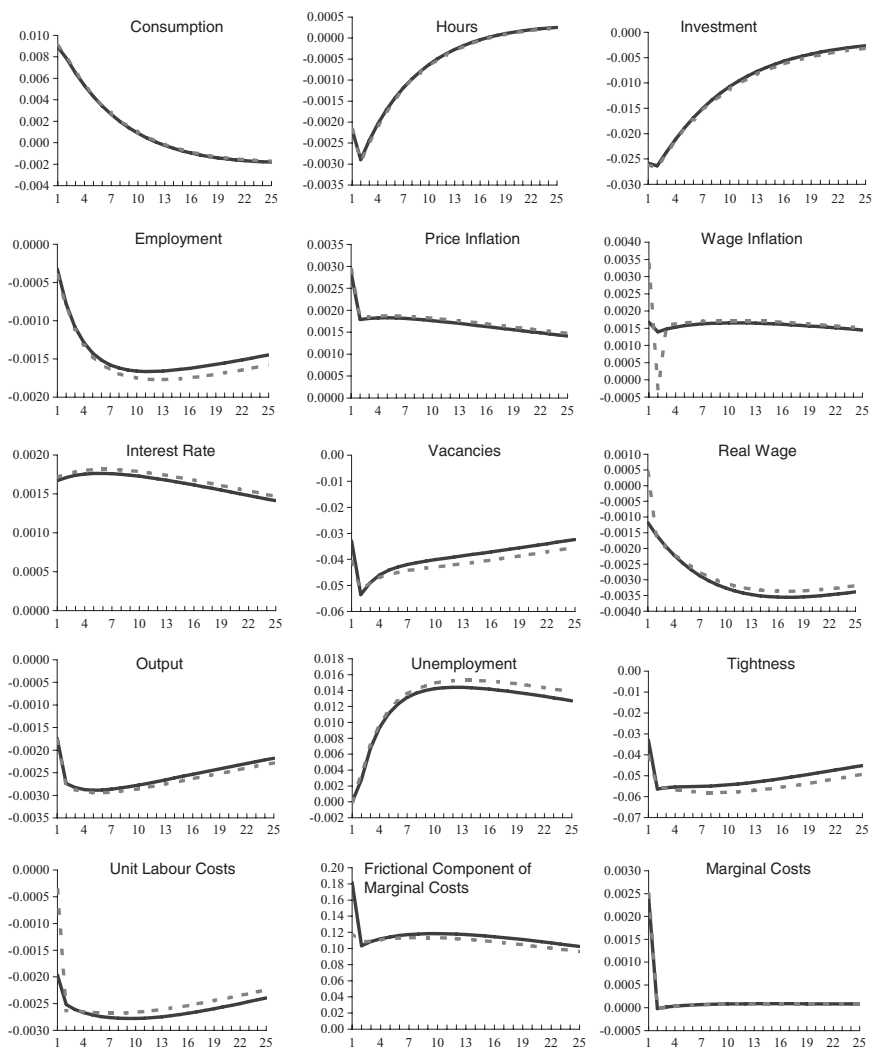
FIG. 5. Impulse Responses to an Investment-specific Technology Shock
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages. Impulse responses are expressed in percentage deviations from the steady state.
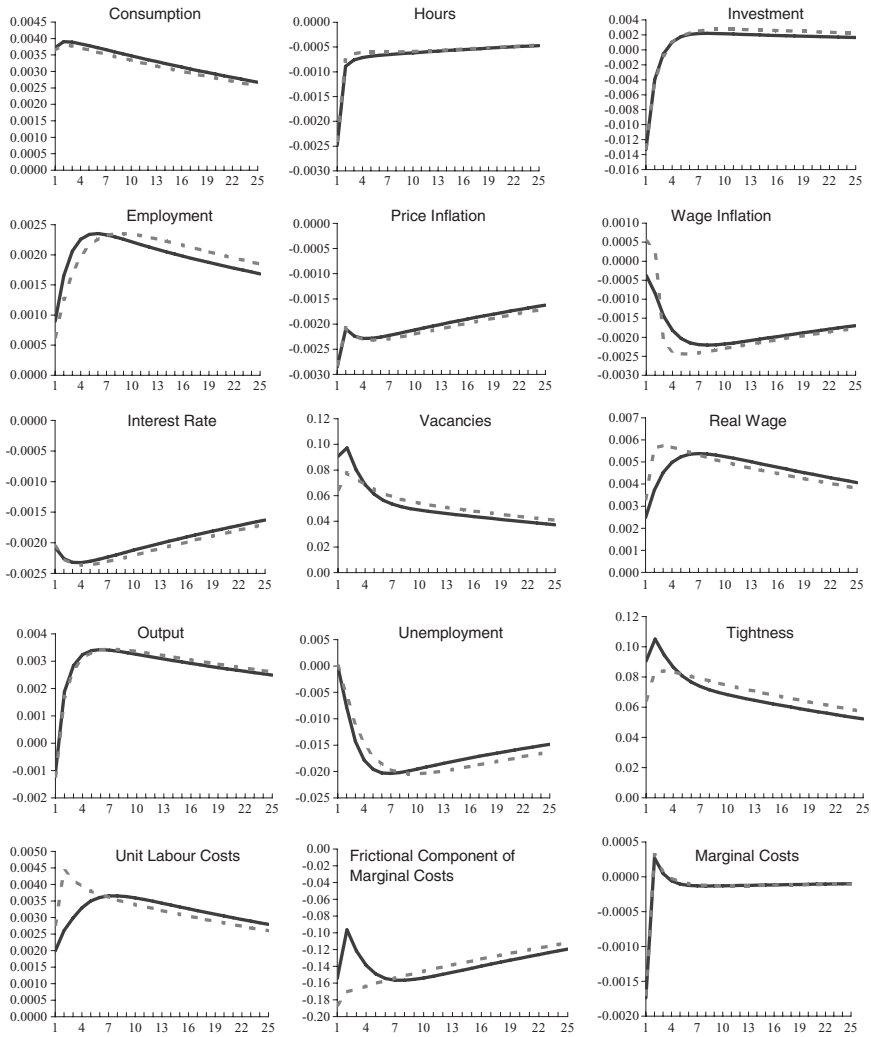
a result, the impact of wage rigidities on the frictional component of marginal costs compensates the impact on unit labour costs, leaving total marginal costs unchanged compared with the case of flexible wages.[14]

Figure 2 shows that in reaction to a one standard deviation neutral technology shock output rises and, due to the downward-sloping demand curve, prices and inflation fall. Lower inflation triggers a lower nominal interest rate, which fosters consumption and investment. The qualitative reactions of these variables are similar in the flexible and staggered wage models. However, the presence of staggered wage setting introduces important differences in the reaction of labour market variables. Following the shock, the increase in real wages is more persistent in the presence of nominal wage rigidities. With sticky wages, price deflation translates into persistently high real wages. With flexible wages, after an initial increase on impact, nominal wages fall sharply, tempering the increase in real wages. It is noticeable that vacancies, employment and labour market tightness increase by less in the presence of sticky wages. The intuition for this is straightforward. A neutral technology shock increases both the marginal product of labour and the real wage. The difference between these two determines the incentives for posting vacancies, as dictated by equation (15). Both with sticky and flexible wages the marginal product of labour increases by more than real wages. With sticky wages, persistently high real wages imply that the present value of a job is lower, which induces the firm to open fewer vacancies.

Figure 3 shows that a one standard deviation monetary policy shock causes an increase in the nominal interest rate, and a fall in both inflation and output. As in the cases of mark-up shocks, nominal wage rigidities do not alter the qualitative responses of the variables on impact, with the exception of the reaction of real wages and unit labour costs. In the presence of sticky wages, vacancies and employment fall in reaction to the shock and price deflation generates higher real wages. When wages are continuously renegotiated instead, nominal wages fall at a faster pace than prices and real wages. Once again nominal wage rigidities have a different impact on unit labour costs in the two settings, whose movements are offset by the reaction of search costs. This generates a remarkably similar response in marginal costs and price inflation in the two settings.

Figure 4 shows impulse responses to a one standard deviation preference shock. The qualitative responses of the variables are the same for the sticky and flexible settings. The preference shock generates an increase in consump-

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[14]Note that one interpretation of this result is that the model is misspecified, therefore implying restrictions on the parameter estimates that undermine the importance of a wage channel. Hence, it would certainly be a valuable task for future research to establish whether the same result holds under alternative specification of the model. Another interpretation of this result is that the series of wages used in the estimation is inaccurate. Hence, it would also be valuable to establish whether the results are robust across different specifications of labour costs.

tion and upward pressure on prices. As price inflation increases, the nominal interest rate rises, and both investment and output fall. The preference shock induces the workers to work a lower number of hours, thereby generating lower return from employment. Hence, the firm posts fewer vacancies, contracting employment and labour market tightness. Finally, also in this instance, nominal wage rigidities do not produce any impact on marginal costs, since search friction costs offset movements in unit labour costs. As a result, inflation dynamics remain substantially unaffected by nominal wage rigidities.

Figure 5 plots impulse responses to a one standard deviation investment-specific technology shock. As in the case of other previous shocks, nominal wage rigidities do not affect the qualitative response of the endogenous variables, with the exception of nominal wage inflation and real wages. An investment-specific technology shock makes investment more efficient. Given that output is demand constrained, due to imperfect competition on the goods market, and the low degree of consumption smoothing makes consumption increase on impact, investment falls. As output gradually increases over time, vacancies and employment increase. Staggered wage negotiations affect the response of nominal wage inflation and the real wage, but as for the other shocks, there is virtually no impact on real marginal costs and price inflation.

To summarize, we find that while wage rigidities might affect the response of labour market variables, they are substantially irrelevant for the dynamics of inflation. This echoes the findings in Krause and Lubik (2007), who reach a similar conclusion in a calibrated model with a wage norm and fewer shocks. This is in stark contrast with the predictions of the standard New Keynesian model without labour market frictions, as in Christiano *et al.* (2005). In their model unit labour costs are the only determinant of marginal costs, implying that wage rigidities naturally generate inflation persistence. Our analysis shows that in a model with search frictions, the contribution of unit labour costs for marginal costs is offset by movements in search costs, which become an additional component of marginal costs.

We assess the ability of the model to match moments of the data by comparing actual data with one-step ahead forecast of inflation, employment, consumption and investment. The model does well at matching employment and consumption. The correlation between predicted employment and actual employment is 0.96, and the standard deviation of the two series is 0.7 per cent and 1 per cent respectively. The correlation between predicted consumption and actual consumption is 0.81, and the standard deviations are 1.5 and 1.7 respectively. The model matches moderately well the second moment of inflation, as the standard deviation of actual and predicted inflation is 0.7 per cent and 0.5 per cent respectively. The correlation between the two series is 0.4. The model does not perform well at matching the correlation between actual and predicted investment, the correlation being –0.33. Predicted investment also appears less volatile than the

TABLE 5
VARIANCE DECOMPOSITION

	Preference	Labour supply	Mark-up	Technology	Monetary policy	Investment	Bargaining
r	35	15	1	4	1	45	0
y	21	16	3	31	3	25	1
π	28	16	1	10	8	35	1
h	9	57	14	3	12	5	1
i	39	13	04	38	3	3	1
n	31	8	2	3	2	43	10
v	20	5	7	3	9	31	24
w/p	25	6	2	5	1	39	22

actual series, as the standard deviation of predicted investment is 3.3 per cent, while the corresponding value in the data is 6.2 per cent. The model is too stylized too match properly investment behaviour.[15]

   To understand the extent to which cyclical movements of each variable are explained by the shocks, Table 5 reports the asymptotic variance decomposition for the model with sticky wages. Entries show that neutral and investment-specific technology shocks explain approximately 60 per cent of fluctuations in output, which is similar to the findings in Gertler *et al.* (2008) on US data. Investment-specific shocks are the main drivers of fluctuations in the nominal interest rate, inflation, employment, vacancies and wages, while labour supply shocks explain approximately 57 per cent of fluctuations in hours. Finally, it is interesting to note that the contribution of preference shocks is sizeable for most variables, while the contribution of mark-up and bargaining shocks is limited. This is due to the high autocorrelation coefficient of 0.88 for the preference shocks and the low autocorrelation coefficients for the mark-up and bargaining shocks, as detailed in Table 3. Tables 6, 7 and 8 report variance decomposition at different horizons for output, employment and inflation.

5   DISCUSSION

From the analysis it clearly emerges that wage rigidities are irrelevant for the dynamics of inflation, similarly to the findings in Krause and Lubik (2007) based on a model calibrated on US data. This result is in contrast to Gertler *et al.* (2008), who estimate a search and matching model with staggered wage setting on US data and detect wage rigidities as important for inflation dynamics. Is our result driven by the specific model that we develop, which

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[15]The root mean squared errors for one step-ahead forecast errors for GDP, inflation and employment are 0.12, 0.08 and 0.31 respectively.

TABLE 6
GDP VARIANCE DECOMPOSITION AT DIFFERENT HORIZONS

	On impact	1 year	4 years	Long run
Preferences	1	4	12	21
Labour supply	5	15	19	16
Price mark-up	7	7	5	3
Technology	79	64	45	31
Monetary policy	8	6	4	3
Bargaining power	0	1	1	1
Investment	0	3	14	25

Note: This table reports the forecast error variance decomposition for output, computed at the mean of the posterior distribution.

TABLE 7
INFLATION VARIANCE DECOMPOSITION AT DIFFERENT HORIZONS

	On impact	1 year	4 years	Long run
Preferences	7	12	21	28
Labour supply	17	22	20	16
Price mark-up	3	3	2	1
Technology	31	24	15	10
Monetary policy	34	25	15	9
Bargaining power	1	2	1	1
Investment	6	13	26	35

Note: This table reports the forecast error variance decomposition for inflation, computed at the mean of the posterior distribution.

TABLE 8
EMPLOYMENT VARIANCE DECOMPOSITION AT DIFFERENT
HORIZONS

	On impact	1 year	4 years	Long run
Preferences	7	12	21	28
Labour supply	17	22	20	16
Price mark-up	3	3	2	1
Technology	31	24	15	10
Monetary policy	34	25	15	9
Bargaining power	1	2	1	1
Investment	6	13	26	35

Note: This table reports the forecast error variance decomposition for employment, computed at the mean of the posterior distribution.

potentially prevents wage rigidities from affecting the dynamics of inflation? Or is it a consequence of the specific estimation of the model?

To answer this question, we simulate the theoretical framework by drawing 1000 times from the parameters posteriors in Table 2 and we compare the variance of inflation from the baseline model with wages rigid-
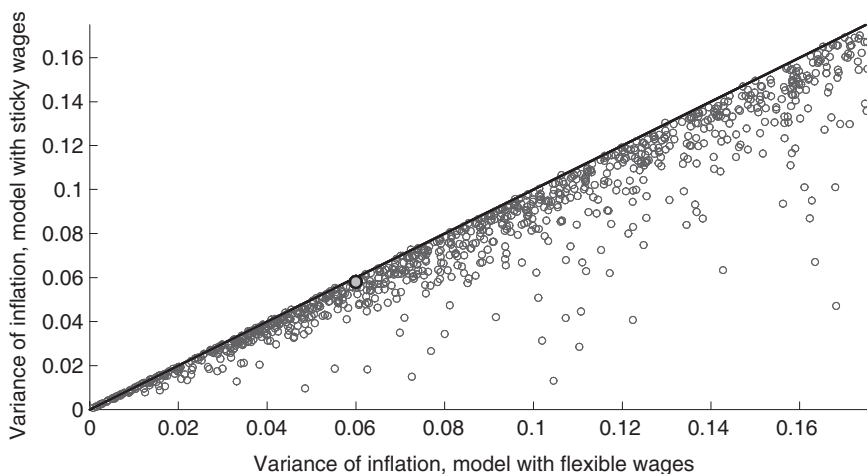
Fɪɢ. 6. Variance of Price Inflation
Notes: The statistics are derived by drawing 1000 times from the parameters priors in Table 2. The *y*-axes reports the variance of inflation in the model with sticky wages, whereas the *x*-axes reports the variance of inflation in the model with flexible wages (i.e. $\delta_w = 0$). The grey dot identifies the variance of inflation in the estimated baseline model and in the otherwise identical model with flexible wages.

ities and an otherwise identical model where the Calvo parameter on wages is set to zero ($\delta_w = 0$). To eliminate extreme responses, we discard the regions of the two distributions below and above 2.5 and 97.5 percentiles respectively. In this way, we are able to establish if the two models deliver the same variance for inflation across a broad range of plausible calibrations, thereby suggesting that the irrelevance result is mechanically generated by the model. Figure 6 reports the scatter plot of the variance of inflation in the model with sticky wages (*y*-axes) against that with flexible wages (*x*-axes), and the 45-degree line indicates the values for which the statistics in the two models are identical. It clearly emerges that most of the scattered points lie below the 45-degree line, suggesting that the variance of inflation in the model with flexible wages is greater than in the model with sticky wages for a wide range of parameters' values. However, for some parameters' values the variance of inflation in the models is identical, since some of the points lie on the 45-degree line. In particular, the grey dot in the figure identifies the variance of inflation in the estimated baseline model and in the otherwise identical model with flexible wages, showing that the two models generate similar statistics.

We can use this analysis to identify which parameters are important for wage rigidities to affect the volatility of inflation. We find that the following two set of parameters play a crucial role. First, the degrees of nominal price and wage rigidities are important. In particular, if wages are more flexible

than prices, the volatility of inflation decreases in the model with sticky wages. This is in line with the findings in Gertler *et al.* (2008) whose estimate of the degree of price rigidities is higher than the degree of wage rigidities, and inflation dynamics are different across the two models. Second, the bargaining power of the worker is an important parameter for the dynamics of inflation across the two models. In particular, a lower bargaining power decreases the volatility of inflation in the model with flexible wages. This is in line with the findings in Erceg *et al.* (2000) who establish that nominal wage rigidities deliver different inflation dynamics to a model with flexible wages in the context of a frictionless labour market.

6 CONCLUSION

We have estimated a New Keynesian model characterized by labour market frictions on UK data to identify some key features of the UK economy. First, we estimated important structural parameters of the British economy, which enabled the investigation of the transmission mechanism of shocks and how it is affected by wage rigidities. We established that neutral and investment-specific technology shocks are important to explain movements in the data. Second, we established that staggered wage setting affects the behaviour of labour market variables and enables the model to fit the data more closely, despite playing an irrelevant role for the dynamics of inflation. In a search and matching model the marginal cost depends on the unit labour cost as well as on the frictional costs of searching. We show that introducing wage rigidities into an otherwise identical model with flexible wages generates offsetting reactions in the frictional costs of employment and in the unit labour cost. As a result, inflation dynamics remain substantially unaffected. This finding echoes the results by Krause and Lubik (2007) but is in contrast to Gertler *et al.* (2008), who find that wage rigidities affect inflation dynamics in an estimated model of the USA. In this paper we show that the irrelevance of wage rigidities for inflation dynamics depends on the parameter estimates of the model, rather than being a feature built into the theoretical model. To reconcile the different findings in the literature future research should investigate the role of the estimated parameter values in determining the link between inflation and marginal costs.

While the results do unveil key features of the UK economy, it should also be noted that the estimation was unable precisely to estimate important labour market parameters of the model, such as the parameters associated with the matching function, which we fixed prior the estimation, calling for refinements to the theoretical setting that could enhance the empirical performance of the model. Furthermore, although the model developed here allows for a variety of supply and demand shocks to have effects on the economy, in practice, a variety of other aggregate shocks may play a role. The

refinement of the theoretical model and the inclusion of additional disturbances remain outstanding tasks for future research.

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