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Abstract

We estimate a New Keynesian model with matching frictions and nominal wage rigidities on UK data. We are able to identify important structural parameters, recover the unobservable shocks that have affected the UK economy since 1971 and study the transmission mechanism. With matching frictions, wage rigidities have limited effect on inflation dynamics, 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.

Key words: DSGE models, Bayesian estimation, labour market search, unemployment.

JEL classification: E24, E32, E52, J64.

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Summary

Dynamic, stochastic, general equilibrium models examine the relationships between economic variables by using economic theory to explain the underlying behaviour of households, firms and the policymaker. They enable us to explore the effects of random ('stochastic') shocks as they work through the economy. Consequently, they have become a powerful tool in the effort to investigate how movements in economic variables relate to the behaviour of inflation. In the New Keynesian framework sticky prices imply that movements in interest rates affect real aggregates and the dynamic behaviour of inflation is driven by the cost to a firm of producing an additional unit of output. This in turn depends crucially on the structure of the labour market. The standard New Keynesian model assumes that firms can immediately adjust employment and hours to whatever levels they wish. But empirical evidence from virtually all the major industrialised countries shows that, in practice, it is costly to adjust either employment or hours as firms have to pay hiring and training costs or overtime payments. These costs will clearly affect the cost of changing output via changes in employment and hours, and so will affect the response of inflation to changes in output. In this paper, we estimate a New Keynesian model characterised by these labour market frictions using UK data and investigate how staggered wage negotiations affect both the response of inflation to changes in economic variables and the ability of the model to fit the data.

In our estimation, we find the degree to which people are willing to work is relatively unresponsive to changes in wages. This low labour supply elasticity reflects the fact that employment is more volatile than average hours. We estimate the ratio of the value of not working to average wages to be about 50%. One feature of the model is that the difficulties of matching jobs to people creates a surplus that is divided between workers and firms in a proportion depending on 'bargaining power' of workers. We find this to be close to 0.9. It follows that wages are close to the marginal product of labour. Another feature is that utility people derive from consumption depends on past consumption, or 'habits', a device that is often used to explain the persistence of economic variables. We find that habit persistence is virtually absent, so the model with frictional labour markets does not need habits to generate persistence in the variables that are made observable to the estimation. We also find that the monetary authority raises interest rates strongly in response to increases in inflation and that they smooth

interest rate changes to a degree.

We establish that staggered wage-setting enables the model to fit the data more closely. Nominal wage stickiness has important implications for labour market dynamics. However, our estimates suggest that wage rigidities are irrelevant for inflation behaviour. Although, following a shock, wage rigidities have a direct effect on unit labour cost, their effect on real marginal cost is offset by the contribution of the component related to labour market frictions. This finding stands in contrast with those obtained in standard New Keynesian models where employment and hours can be adjusted immediately and without cost. In the absence of these costs, the dynamics of inflation are only driven by the unit labour costs and so wage rigidities will automatically generate inflation persistence by making unit labour costs more persistent.

Finally, the estimated model also allows us to assess what economic factors are driving UK economic fluctuations. We find that neutral and investment-specific technology shocks are important to explain fluctuations in the data. And, we are able to provide evidence that the volatility of aggregate shocks has somewhat decreased from the mid-1990s until the mid-2000s. These findings suggest that the 'Great Moderation' in macroeconomic volatility in the United Kingdom between the early 1990s and 2008 might have resulted from a lower volatility of shocks during the past decade.

While our results do unveil key features of the UK economy, it should be noted that we were unable precisely to estimate some important parameters of the model, such as the degree of nominal wage stickiness. This suggests a need to refine the model in ways that could improve its empirical performance. 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. Nevertheless, the model advances our understanding of UK inflation dynamics.

1 Introduction

Dynamic, stochastic, general equilibrium 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. However, empirical evidence from virtually all the major industrialised countries, as surveyed by Bean (1994) and Nickell (1997), shows that labour markets are characterised by frictions that prevent the competitive allocation of resources. 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. A growing number of empirical studies document that embedding labour market frictions into a standard New Keynesian model increases the model's empirical performance and enables a more accurate description of inflation dynamics.[2]

The contribution of our paper is two-fold. First, we build on these previous studies to estimate a New Keynesian model characterised by labour market frictions using UK data. This estimation allows us to estimate the structural parameters of the United Kingdom economy, the unobservable shocks and study their transmission mechanism. Second, we investigate how staggered 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 particular, 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 of the labour

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[1] See Smets and Wouters (2003, 2007) for an extensive application of this framework.

[2] Noticeable examples, documented below, are Gertler *et al* (2008), Christoffel, Kuester and Linzert (2009), Krause *et al* (2008b), Zanetti (2010) and Ravenna and Walsh (2008).

market that characterise 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 estimate of the ratio of the income value of non-working activity over wages is approximately 51%, which casts doubt on the argument by Hagedorn and Manovskii (2008) that a high opportunity cost of working - eg, over 90% - be a plausible solution of the unemployment volatility puzzle in the United Kingdom. Gertler *et al* (2008) find results similar to ours using US data. The bargaining power of the workers is estimated to equal about 0.9, a considerably high value, while the habit persistence parameter is close to zero. We also provide estimates for the monetary authority's reaction function. We find that the monetary authority's response to inflation is particularly strong, there is a mild degree of interest rate inertia and a weak response to output fluctuations.

The estimated model allows us to characterise 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. Finally, using a Kalman filter on the model's reduced form we provide estimates for the unobservable shocks that characterised the post-1970s' British economy. In general, we find that the magnitude of some shocks has somewhat decreased in the period between the mid-1990s and the mid-2000s. In particular, similarly to studies for other countries, we find that the volatility of monetary policy shocks declined during this period. These findings corroborate the results of empirical studies, such as Benati (2007) and Bianchi *et al* (2009), which detected a period of macroeconomic stability triggered by a lower volatility of shocks in the United Kingdom during the same time span.

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, that is, 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. We elaborate more on the intuition in the main text. This result holds for all the shocks in our model economy and stands in sharp contrast with those obtained in

a 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)).

The paper is related to several studies. As in Krause and Lubik (2007), Krause *et al* (2008a,b), Ravenna and Walsh (2008) and Zanetti (2010), we internalise 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, marginal costs will only depend on hours. But when hours are efficiently bargained the number of hours will depend only on the ratio between marginal rate of substitution and the marginal product of labour, which in turn are independent from 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 Kuester (2008), Christoffel and Linzert (2006), Christoffel, Kuester and Linzert (2009), Mattesini and Rossi (2008) and Zanetti (2010)). 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. 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 organised 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. Finally, Section 5 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 $M(U_t, V_t) = m U_t^\xi V_t^{1-\xi}$, 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. Consequently, the evolution of aggregate employment N_t is:[4]

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

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

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[3] Note that $U_t = \int_0^1 u_{jt} dj$ and $V_t = \int_0^1 v_{jt} dj$.
[4] Note that $N_t = \int_0^1 n_{jt} dj$.

evolution of aggregate unemployment is written:

$$U_t = 1 - (1 - \rho)N_{t-1}.$$

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 maximise an expected utility function of the form

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

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:

$$c_t = \left(\int_0^1 c_t(j)^{(\epsilon_t - 1)/\epsilon_t} dj \right)^{\epsilon_t/(\epsilon_t - 1)},$$

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 minimising price index associated with the representative consumption bundle c_t is:

$$p_t = \left(\int_0^1 p_t(j)^{1-\epsilon_t} dj \right)^{1/(1-\epsilon_t)}.$$

The household faces the following budget constraint:

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

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} from previous period $t-1$ which pay a gross nominal interest rate R_{t-1}, the proceedings from working in the firms indexed by j, $\int_0^1 \omega_{jt} n_{jt} h_{jt} dj$, and the unemployed benefits, b, earned by each unemployed member of the household. In addition, the household earns proceedings from renting capital, k_t, to the firms at the rate r_t^k, the 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 maximise the utility function (2), subject to the budget constraint in equation (3) and the law of motion for capital,

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

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:

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

$$\lambda_t = \beta E_t \left[\lambda_{t+1} R_t / \pi_{t+1}) \right], \tag{6}$$

$$\lambda_t = \beta E_t \lambda_{t+1} \left[r_{t+1}^k + (1 - \delta_k) \right], \tag{7}$$

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_{jt}^E, is given by:

$$W_{jt}^E = \lambda_t \omega_{jt} h_{jt} - \zeta_t \chi_t \frac{h_{jt}^{1+\mu}}{1+\mu} + \beta E_t \lambda_{t+1} \left[\rho W_{t+1}^U + (1-\rho) W_{jt+1}^E \right], \tag{8}$$

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_t^U, is:

$$W_t^U = \lambda_t b + \beta E_t \lambda_{t+1} \left[(1 - \theta_{t+1} q(\theta_{t+1})) W_{t+1}^U + (1-\rho) \theta_{t+1} q(\theta_{t+1}) \hat{W}_{t+1}^E \right], \tag{9}$$

where $E_t \hat{W}_{t+1}^E = \int_0^1 W_{jt+1}^E dj$ 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, $W_{jt}^E - W_t^U$, denoted by W_{jt}, as:

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

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.

Producers

There is a continuum of producers of unit measure selling homogeneous goods at the competitive price φ_t. During each period, firm j manufactures y_{jt} units of goods according to the following production technology $y_{jt} = A_t \left(n_{jt} h_{jt} \right)^\alpha k_{jt}^{1-\alpha}$, 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 equalised 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 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 maximise the present value of future discounted profits:

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

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

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

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:

$$r^k_t = \varphi_t (1 - \alpha) A_t \left(n_{jt} h_{jt} \right)^{\alpha} k_{jt}^{-\alpha}, \tag{12}$$

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

$$J_{jt} = \varphi_t \alpha A_t \left(n_{jt} h_{jt} \right)^{\alpha - 1} k_{jt}^{1-\alpha} h_{jt} - \omega_{jt} h_{jt} + \beta (1 - \rho) E_t \frac{\lambda_{t+1}}{\lambda_t} J_{jt+1}. \tag{14}$$

Equation **(12)** implies that returns to capital equalise 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, ie, 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:

$$\frac{\mathcal{C}'(v_{jt})}{q(\theta_t)} = \varphi_t \alpha A_t \left(n_{jt} h_{jt} \right)^{\alpha - 1} k_{jt}^{1-\alpha} h_{jt} - \omega_{jt} h_{jt} + \beta (1 - \rho) E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{\mathcal{C}'(v_{jt+1})}{q(\theta_{t+1})}, \tag{15}$$

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

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

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

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 maximise:

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

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

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

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 $\epsilon_t / (\epsilon_t - 1)$. Since firms are randomly selected to change price, the law of motion for the aggregate price level is:

$$p_t^{1-\epsilon_t} = \delta_p p_{t-1}^{1-\epsilon_t} + (1 - \delta_p) \left(p_t^*\right)^{1-\epsilon_t}. \qquad (18)$$

2.4 Wage bargaining

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

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

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 maximise 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 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:

$$\frac{W_{jt}^*}{\lambda_t} = \omega_{jt}^* h_{jt} - \tilde{\omega}_{jt} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1-\rho)\left[\delta_w \frac{W_{jt+1|t}}{\lambda_{t+1}} - (1-\delta_w)\frac{W_{jt+1}^*}{\lambda_{t+1}}\right], \qquad (20)$$

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

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

The net value of employment to the household conditional on wage renegotiation at time t (equation **(20)**), equals the net flow income from employment, $\omega_{jt}^* h_{jt} - \tilde{\omega}_{jt}$, 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 $1-\delta_w$. Similarly, the shadow value of employment to the renegotiating firm j can be written:

$$J_{jt}^* = \bar{\omega}_{jt} - \omega_{jt}^* h_{jt} + (1-\rho)E_t \frac{\lambda_{t+1}}{\lambda_t}\left[\delta_w J_{jt+1|t} + (1-\delta_w)J_{jt+1}^*\right], \qquad (21)$$

where $\bar{\omega}_{jt} = \varphi_t mpl_t h_{jt}$ 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 it is possible to rewrite them as follows:

$$\frac{W_{jt}^*}{\lambda_t} = E_t \sum_{s=0}^{\infty}\beta^s \frac{\lambda_{t+s}}{\lambda_t}(1-\rho)^s \delta_w^s \left(\omega_{jt}^* h_{jt+s} - \tilde{\omega}_{jt+s}\right)$$

$$+(1-\rho)(1-\delta_w)E_t \sum_{s=0}^{\infty}\beta^{s+1}\frac{\lambda_{t+s+1}}{\lambda_t}(1-\rho)^s \delta_w^s \frac{W_{jt+s+1}^*}{\lambda_{t+s+1}}, \qquad (22)$$

$$J_{jt}^* = E_t \sum_{s=0}^{\infty} \beta^s \frac{\lambda_{t+s}}{\lambda_t}(1-\rho)^s \delta_w^s \left(\bar{\omega}_{jt+s} - \omega_{jt}^* h_{jt+s}\right)$$

$$+(1-\rho)(1-\delta_w)E_t \sum_{s=0}^{\infty} \beta^{s+1} \frac{\lambda_{t+s+1}}{\lambda_t}(1-\rho)^s \delta_w^s J_{jt+s+1}^*. \tag{23}$$

Using the sharing rule in equation **(19)**, **(22)** and **(23)** imply that:

$$E_t \sum_{s=0}^{\infty} \beta^s \frac{\lambda_{t+s}}{\lambda_t}(1-\rho)^s \delta_w^s \left(\omega_{jt}^* h_{jt+s} - \omega_{t+s}^{tar}\right) = 0, \tag{24}$$

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

$$\omega_{jt+s}^{tar} = \eta_t \varphi_t mpl_t h_{jt} + (1-\eta_t)\left[b + \frac{\zeta_t \chi_t}{\lambda_t}\frac{h_{jt}^{1+\mu}}{1+\mu} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1-\rho)\theta_{t+1}q(\theta_{t+1})\frac{\hat{W}_{t+1}}{\lambda_t} \right]. \tag{25}$$

Equation **(25)** 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 wage is given by:

$$\omega_t = \delta_w \omega_{t-1} + (1-\delta_w)\omega_t^*, \tag{26}$$

where $\omega_t = \int_0^1 \omega_{jt}dj$.

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:

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

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 equalised across firms at equilibrium, it follows that members of the household employed in different firms work

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the same amount of hours, ie, $h_{jt} = h_t$. Solving the first-order condition for hours yields:

$$h_{jt} = \eta_t \left(\frac{\varphi_t A_t \alpha^2 n_{jt}^{\alpha-1} k_{jt}^{1-\alpha}}{\chi_t \zeta_t} \lambda_t \right)^{\frac{1}{1+\mu-\alpha}}. \qquad (27)$$

2.6 Price and wage inflation

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

$$\pi_t = k_p \left(\hat{\varphi}_t + \epsilon_t \right) + \beta E_t \pi_{t+1}, \qquad (28)$$

where a hat superscript denotes the variable's deviation from its steady state, and the coefficient k_p is equal to:

$$k_p \equiv \frac{\left(1 - \beta \delta_p \right) \left(1 - \delta_p \right)}{\delta_p}.$$

Similarly, following Thomas (2008), using equations **(24)** and **(26)** we obtain the following equation for wage inflation:

$$\pi_{wt} = k_w \left[\hat{\omega}_t^{tar} - \left(\hat{\omega}_t + \hat{h}_t \right) \right] + \beta \left(1 - \rho \right) E_t \pi_{wt+1}, \qquad (29)$$

where the coefficient k_w is equal to:

$$k_w \equiv \frac{\left[1 - \beta \left(1 - \rho \right) \delta_w \right] \left(1 - \delta_w \right)}{\delta_w}.$$

Equation **(29)** states that wage inflation depends on the gap between the actual and target real wage bill, $\hat{\omega}_t + \hat{h}_t$ and $\hat{\omega}_t^{tar}$, respectively. Inflation materialises whenever the real wage bill is below target, that is, whenever the wage bill is below the level that would prevail if wages were perfectly flexible. The appendix reports the derivation of the wage Phillips curve, equation **(29)**.

2.7 Closing the model

The monetary authority sets the nominal interest rate following the Taylor rule:

$$\frac{R_t}{R^*} = \left(\frac{R_{t-1}}{R^*} \right)^{\rho_r} \left[\left(\frac{\pi_t}{\pi^*} \right)^{r_\pi} \left(\frac{y_t}{y^*} \right)^{r_y} \right]^{1-\rho_r} \varepsilon_t^R,$$

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 i.i.d. monetary policy shock.

The fiscal authority is assumed to run a balanced budget:

$$\frac{B_t}{p_t} = R_{t-1} \frac{B_{t-1}}{p_t} + T_t + b\,(1 - n_t)\,.$$

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. Trigari (2006) shows that whenever firms post vacancies at time t to control employment in the following period, the matching model with efficient bargaining on hours lacks an instantaneous transmission channel from wages to prices since the real marginal cost is independent from wages at time t. 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 from wages in the current period t. It follows that current wages are irrelevant for marginal costs.

Following Trigari (2006), a number of authors such as Christoffel and Kuester (2008), Christoffel and Linzert (2006), Mattesini and Rossi (2009) 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:

$$\varphi_t = \frac{\omega_t h_t}{mpe_t} + \frac{J_t - \beta E_t \frac{\lambda_{t+1}}{\lambda_t} (1 - \rho) J_{t+1}}{mpe_t}, \tag{30}$$

where $mpe_t = A_t \alpha \left(n_{jt} h_{jt}\right)^{\alpha - 1} k_{jt}^{1-\alpha} h_{jt}$ denotes the marginal product of employment. From equation **(30)**, 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 **(30)** 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. If we had 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 from wages.

3 Estimation

The model is estimated with Bayesian methods. It is first loglinearised 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. 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. 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. 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 1,600.

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. 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 $\ln \kappa_{t+1} = \rho_{\kappa} \ln \kappa_t + \upsilon_t$, where the shock $\kappa \in \{\zeta, \chi, \epsilon, A, \phi, \varepsilon^{\eta}\}$, $0 < \rho_{\kappa} < 1$ and $\upsilon_t \sim N(0, \sigma_{\kappa})$. Monetary policy shocks ε_t^R are i.i.d.

The model contains 19 structural parameters, excluding the shock parameters. A first attempt to estimate the model showed that the estimation procedure was unable to provide plausible estimates for some structural parameters. As in other similar studies, we calibrated these parameters in order to match important stylised facts in the data. We start by discussing the fixed parameters, whose values are summarised in Table A. The discount factor β is set at 0.99 implying a real interest rate of 4%. 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%. 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 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 B and C report priors, posterior estimates and 90% confidence intervals for the structural and shock parameters respectively.

The prior means of the relative risk aversion, σ, the index of external habit, ς, and the inverse of the Frisch elasticity of labour supply, μ, are set equal to 0.66, 0.5 and 1 respectively, as in Smets and Wouters (2007) and Gertler *et al* (2008). The prior mean for the unemployment benefits coefficient, b, is calibrated to match a replacement ratio of 0.38 as in Nickell (1997). 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 this case the surplus of a job is very

small and tiny changes in the productivity of the labour input produce a high change in the total surplus of a match, boosting the response of employment. However, as detailed below, Costain and Reiter (2008) show that a high value of *b* is empirically implausible. For this reason we choose a prior value for *b* which is low enough not to generate an additional source of amplification.

The prior mean of 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%, in line with evidence from the Labour Force Survey (LFS). The prior mean of the job destruction rate, ρ, is set to 0.03, as estimated by Bell and Smith (2002) using LFS data. 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% 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 wages, δ_ω, is set to 0.75 in order to match a yearly average wage renegotiation frequency, as in Dickens *et al* (2007). Similarly, 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. 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%.

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, 0.5 and 0.5 respectively. These values are commonly used in the literature.

Finally, Table C 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. These priors are similar to those in Smets and Wouters (2007) and Gertler *et al* (2008).

3.2 Parameter estimates

The third, fourth and fifth columns of Table B show the posterior means of the structural parameters together with their 90% confidence intervals. The posterior mean of the relative risk aversion σ is equal to 0.72, similar to the estimate in Smets and Wouters (2007) for the United States. 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. 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 United States, although their estimate is higher than ours. The posterior mean of the unemployment benefit parameter b is equal to 0.38, in line with the microeconomic estimates for the UK economy.

The posterior mean of the elasticity of the matching function ξ is equal to 0.71, close to its prior mean, which suggests that the model is unable to precisely estimate this parameter. The posterior mean of the constant of the matching function m is equal to 0.64, which implies a job-finding rate of 30%, similar to the estimate of the data. The posterior mean of the rate of job separations ρ is equal to 3.3%, also in line with UK data. The posterior mean of the constant of the vacancy cost function a is equal to 2.7, lower than its prior, which indicates that the model prefers a low cost of posting a vacancy, which is equal to 0.4% of output at the estimated equilibrium. The posterior mean of the bargaining power of the workers η is equal to 0.89, thereby indicating that wages are closer to the marginal product of labour.

The posterior means of the Calvo parameters on the frequency of wage and price negotiations, δ_ω and δ_p, are equal to 0.76 and 0.44 respectively, showing that prices adjust more frequently than wages. These values imply an average frequency of wage negotiations of one year, in line with Dickens *et al* (2007), and an average frequency of price negotiations of five months, in line with Bunn and Ellis (2009) for the UK economy. However, although the model prefers higher wage rigidities than price rigidities, the estimation procedure is unable to precisely estimate the Calvo wage parameter, therefore leaving a sizable uncertainty around its posterior mean.

The posterior mean of the elasticity of demand ϵ is equal to 11.6, implying a price mark-up of approximately 9%, similar to the UK estimates in Britton *et al* (2000). Finally, the estimates of the Taylor rule parameters are as follows. The posterior mean of the interest rate response to inflation, r_π, equal to 1.46 indicates a strong response to inflation and the posterior mean of the degree of interest rate smoothing, ρ_r, equal to 0.54 suggests a mild degree of interest rate inertia. The posterior mean of the response to output, r_y, equal to 0.34 shows a weak response to output.

The third, fourth and fifth columns of Table C show the posterior means of the shock parameters together with their 90% confidence intervals. The posterior means of the persistence parameters ρ_χ and ρ_ζ, equal to 0.83 and 0.87 respectively, indicate that shocks to the labour supply and preferences are substantially more persistence than the other shocks. The posterior means of the shocks' variance is close to 1% for all the shocks, with the exception of investment-specific technology shocks, σ_a, and bargaining shocks, σ_η, which are more volatile.

In order to establish whether staggered wages are important to match the data, Table D reports the value of the marginal likelihood function for the estimated models with sticky and flexible wages respectively. Since the value of the marginal likelihood function associated with the model with sticky wages is equal to 3,451, and higher then the value 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, variance decomposition and unobserved shocks

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 ($\delta_\omega = 0$).

Figures 1-7 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). 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 to 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.[5] The rising profile in expected search costs implies that the firm can save on future hiring costs by increasing current period hiring. From equation **(30)**, higher expected search costs next period, translate in lower marginal costs in the current period. As 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 to the case of flexible wages.

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

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[5]Note that the average duration of a vacancy, $1/q(\theta_t)$, depends only on labour market tightness.

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 labour supply shock reduces hours and exerts upward pressure on nominal wages by increasing the disutility of work. With flexible nominal wages, real wages increase, leading to a reduction in vacancies and employment. On the contrary, with staggered wage bargaining nominal wage inflation is lower than price inflation, which implies that real wages fall. Consequently, in the sticky wage model, vacancies and employment increase. Wage rigidities do not have a significant impact on marginal costs and inflation since the effect produced through unit labour costs is offset by the effect of the frictional component of marginal costs.

Figure 4 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 reaction to the shock, vacancies and employment fall, while in the presence of sticky wages 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 5 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 consumption 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.

As shown in Figure 6, also in the case of a one standard deviation bargaining power shock, the qualitative reaction of labour market variables is unchanged by wage rigidities. Higher bargaining power increases wage and price inflation. The real wage increases, and consequently vacancies fall. A higher interest rate decreases consumption and investment, which triggers a fall in output. Staggered wage negotiations dampen the reaction of both nominal and real wages and, as a result, of unit labour costs. However, also in this instance, the reaction of the frictional component of marginal costs largely offsets the impact of wage rigidities on unit labour costs, thereby generating a similar inflation dynamics across the two models.

Figure 7 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 summarise, 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.

To understand the extent to which cyclical movements of each variable are explained by the shocks, Table E reports the asymptotic variance decomposition for the model with sticky wages.

Entries show that neutral and investment-specific technology shocks explain approximately 60% 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 and vacancies, while labour supply shocks explain approximately 67% 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 0.87 for the preference shocks and the low autocorrelation coefficients for the mark-up and bargaining shocks, as detailed in Table C.

To detail how the exogenous shocks have evolved during the sample period, Figure 6 plots the estimates of the shocks using the Kalman smoothing algorithm from the state-space representation of the model with sticky wages. The estimates show that the magnitude of shocks has somewhat decreased from mid-1990s until mid-2000s, with the exception of labour supply shocks, whose size has remained broadly unchanged. Furthermore, similarly to studies for other countries, we find that the volatility of monetary policy shocks declined during the same period. These findings corroborate the results of empirical studies, such as Benati (2007) and Bianchi *et al* (2009), which detected a period of macroeconomic stability triggered by a lower volatility of shocks in the United Kingdom during the same time horizon.

5   Conclusion

We have estimated a New Keynesian model characterised 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. In addition, using a Kalman filter on the model's reduced form we provided estimates for the unobserved shocks that characterised the post-1970s British economy. Similarly to studies for other countries, we found that the volatility of shocks declined in the period from the mid-1990s until the mid-2000s, corroborating the evidence that this factor might have contributed to the macroeconomic stability in that period.

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 United States. This discrepancy suggests that 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 parameters of the model, such as the degree of nominal wage adjustments, 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.

6 Appendix A

Derivation of the wage Phillips curve.

A first-order Taylor expansion on **(24)** yields:

$$E_t \sum_{s=0}^{\infty} \beta^s (1-\rho)^s \delta_w^s \left(\log \omega_{jt}^* h_{jt+s} \log \omega h - \hat{\omega}_{jt+s|t}^{tar} \right) = 0. \tag{31}$$

Notice from equation **(25)** in the text that $\hat{\omega}_{jt}^{tar} = \hat{\omega}_t^{tar}$. If $\hat{\omega}_{jt}^{tar} = \hat{\omega}_t^{tar}$, then equation **(24)** implies that $\omega_{jt}^* = \omega_t^*$.

Equation **(31)** can be rewritten solving for ω_t^*, and expressing the solution recursively:

$$\log \omega_t^* = [1 - \beta (1-\rho) \delta_w] \left(\hat{\omega}_t^{tar} - \log h_t + \log \omega h \right) + \beta (1-\rho) \delta_w E_t \log \omega_{t+1}^*. \tag{32}$$

The law of motion of the wage index in equation **(26)** can be rewritten as follows:

$$\log \omega_t^* - \log \omega_{t-1} = \pi_{wt}, \tag{33}$$

where $\pi_{wt} = \log \omega_t - \log \omega_{t-1}$. Using **(33)**, equation **(31)** can be rewritten as:

$$\pi_{wt} = k_w \left(\hat{\omega}_t^{tar} - \hat{\omega}_t - \hat{h}_t \right) + \beta (1-\rho) E_t \pi_{wt+1},$$

where $k_w = [1 - \beta (1-\rho) \delta_w] (1 - \delta_w) / \delta_w$.

7 Appendix B

The log-linear equilibrium conditions:

Euler equations

$$\hat{\lambda}_t = \hat{\lambda}_{t+1} + r_t - \pi_{t+1}$$

$$\hat{\lambda}_t = \zeta_t - [\sigma / (1 - \varsigma)] \left(\hat{c}_t - \varsigma \hat{c}_{t-1} \right)$$

$$\hat{\lambda}_t = \hat{\lambda}_{t+1} + \beta (1-\alpha) \frac{\varphi}{\lambda} \frac{\hat{y}}{\hat{k}} \left(\hat{\varphi}_{t+1} - \hat{\lambda}_{t+1} + \hat{y}_{t+1} - \hat{k}_{t+1} \right)$$

Production function

$$\hat{y}_t = \hat{A}_t + \alpha \left(\hat{n}_t + \hat{h}_t \right) + (1-\alpha) \hat{k}_t$$

Resource constraint

$$\hat{y}_t = \left(\frac{c}{y} \right) \hat{c}_t + \frac{\varepsilon_c c \upsilon^{\varepsilon_c}}{y} \hat{\upsilon}_t + \frac{i}{y} \hat{\imath}_t$$

Unemployment

$$\hat{u}_t = -(1 - \rho)\frac{n}{u}\hat{n}_{t-1}$$

Employment

$$\hat{n}_t = (1 - \rho)\hat{n}_{t-1} + \rho\left[\xi\hat{u}_t + (1 - \xi)\hat{v}_t\right]$$

Tightness

$$\hat{\theta}_t = \hat{v}_t - \hat{u}_t$$

Investment

$$\frac{i}{k}\left(\hat{\imath}_t + \phi_t\right) = \hat{k}_{t+1} - (1 - \delta_k)\hat{k}_t$$

Job creation

$$\frac{\varepsilon_c c v^{\varepsilon_c - 1}\theta^\xi}{m}\left[(\varepsilon_c - 1)\hat{v}_t + \xi\hat{\theta}_t\right] = \alpha\frac{\varphi}{\lambda}\frac{y}{n}\left(\widehat{mc}_t - \hat{\lambda}_t + \hat{y}_t - \hat{n}_t\right) - \omega h\left(\hat{\omega}_t + \hat{h}_t\right)$$

$$+ (1 - \rho)\beta\frac{\varepsilon_c c v^{\varepsilon_c - 1}\theta^\xi}{m}\left[(\varepsilon_c - 1)\hat{v}_{t+1} + \xi\hat{\theta}_{t+1} + \hat{\lambda}_{t+1} - \hat{\lambda}_t\right]$$

Target wage bill

$$\hat{\omega}_t^{tar} = \frac{1}{\omega h}\left[\eta\varphi mpe\left(\hat{\varphi}_t + \widehat{mpe}_t + \eta_t\right) + (1 - \eta)\frac{h^{1+\mu}}{1 + \mu}\frac{1}{\lambda}\left(\hat{\zeta}_t + \hat{\chi}_t - \hat{\lambda}_t + (1 + \mu)\hat{h}_t\right)\right]$$

$$-\eta(b + \frac{1}{\lambda}\frac{h^{1+\mu}}{1 + \mu})\eta_t + \eta(1 - \rho)\beta\varepsilon_c c v^{\varepsilon_c - 1}\theta\left[\hat{\lambda}_{t+1} - \hat{\lambda}_t + \hat{\theta}_{t+1} + (\varepsilon_c - 1)\hat{v}_{t+1} + \eta_t\right]$$

Hours

$$\hat{h}_t = \frac{1}{(1 + \mu - \alpha)}\left[\hat{\varphi}_t + \hat{A}_t + (\alpha - 1)\hat{n}_t + (1 - \alpha)\hat{k}_t + \hat{\lambda}_t - \hat{\zeta}_t - \hat{\chi}_t\right]$$

Marginal product of employment

$$\widehat{mpe}_t = \hat{A}_t + (1 - \alpha)\left(\hat{k}_{t-1} - \hat{n}_t\right) + \alpha\hat{n}_t$$

Average real wage

$$\hat{\omega}_t - \hat{\omega}_{t-1} + \pi_t = \pi_{wt}$$

Wage inflation

$$\pi_{wt} = k_w\left(\hat{\omega}_t^{tar} - \hat{\omega}_t - \hat{h}_t\right) + \beta\pi_{t+1}$$

Price inflation

$$\pi_t = k_p\left(\hat{\varphi}_t + \hat{\epsilon}_t\right) + \beta\pi_{t+1}$$

Taylor rule

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)\left(r_\pi\pi_t + r_y\hat{y}_t\right) + \hat{\varepsilon}_t^R$$

8 Tables and figures

Table A: 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	1.10

Table B: Prior and posterior distribution of structural parameters distributions

	Description	Prior mean	Post. mean	5%	95%	Prior dist	Prior SD
σ	Relative risk aversion	0.66	0.72	0.60	0.85	*gamma*	0.20
ς	Habit persistence	0.5	0.04	0.01	0.07	*beta*	0.2
μ	Inverse Frisch elasticity	1	1.62	1.49	1.77	*gamma*	0.1
b	Unemployment benefits	0.38	0.39	0.24	0.53	*beta*	0.10
ξ	Matching function elasticity	0.7	0.71	0.65	0.78	*beta*	0.05
m	Constant matching function	0.5	0.64	0.51	0.77	*gamma*	0.10
ρ	Job destruction rate	0.03	0.033	0.020	0.042	*beta*	0.01
a	Const. vacancy cost function	3	2.7	1.6	3.6	*gamma*	1.00
η	Workers' bargaining power	0.5	0.89	0.84	0.96	*beta*	0.2
δ_ω	Calvo wage parameter	0.75	0.76	0.56	1.00	*beta*	0.20
δ_p	Calvo price parameter	0.5	0.44	0.17	0.75	*beta*	0.20
ϵ	Elasticity of demand	11	11.6	9.05	13.50	*gamma*	1.00
r_π	Taylor rule resp. to inflation	1.5	1.48	1.42	1.54	*gamma*	0.05
r_y	Taylor rule resp. to output	0.5	0.34	0.29	0.39	*gamma*	0.05
ρ_r	Taylor rule inertia	0.5	0.54	0.52	0.57	*beta*	0.02

Table C: Prior and posterior distribution of shock parameters

	Description	Prior mean	Posterior mean	5%	95%	Prior dist	Prior SD
Autoregressive parameters:							
ρ_χ	Labour supply	0.8	0.83	0.78	0.87	*beta*	0.2
ρ_ζ	Preferences	0.8	0.87	0.82	0.92	*beta*	0.2
ρ_ϵ	Mark-up	0.8	0.36	0.29	0.44	*beta*	0.2
ρ_a	Technology	0.8	0.24	0.17	0.31	*beta*	0.2
ρ_i	Investment	0.8	0.44	0.21	0.62	*beta*	0.2
ρ_η	Bargaining	0.8	0.15	0.06	0.23	*beta*	0.2
Standard errors:							
σ_χ	Labour supply	0.002	0.019	0.016	0.022	*inv gamma*	0.300
σ_ζ	Preferences	0.002	0.008	0.007	0.010	*inv gamma*	0.300
σ_ϵ	Mark-up	0.002	0.008	0.007	0.009	*inv gamma*	0.300
σ_a	Technology	0.002	0.018	0.016	0.020	*inv gamma*	0.300
σ_ε	Monetary policy	0.002	0.06	0.005	0.007	*inv gamma*	0.300
σ_i	Investment	0.002	0.189	0.130	0.250	*inv gamma*	0.300
σ_η	Bargaining	0.002	0.239	0.184	0.291	*inv gamma*	0.300

Table D: Marginal likelihood function

Sticky wages	3451
Flexible wages	2944

Table E: Variance decomposition

	Preference	Labour supply	Mark-up	Technology	Monetary policy	Investment	Bargaining
r	0.34	0.13	0.00	0.03	0.01	0.47	0.01
y	0.18	0.15	0.2	0.41	0.02	0.22	0.01
π	0.26	0.15	0.01	0.13	0.11	0.33	0.01
h	0.10	0.67	0.07	0.07	0.06	0.04	0.02
i	0.38	0.12	0.02	0.45	0.02	0.02	0.00
n	0.28	0.04	0.01	0.02	0.06	0.48	0.10
υ	0.19	0.04	0.05	0.04	0.15	0.37	0.17

Figure 1: Impulse responses to a mark-up shock
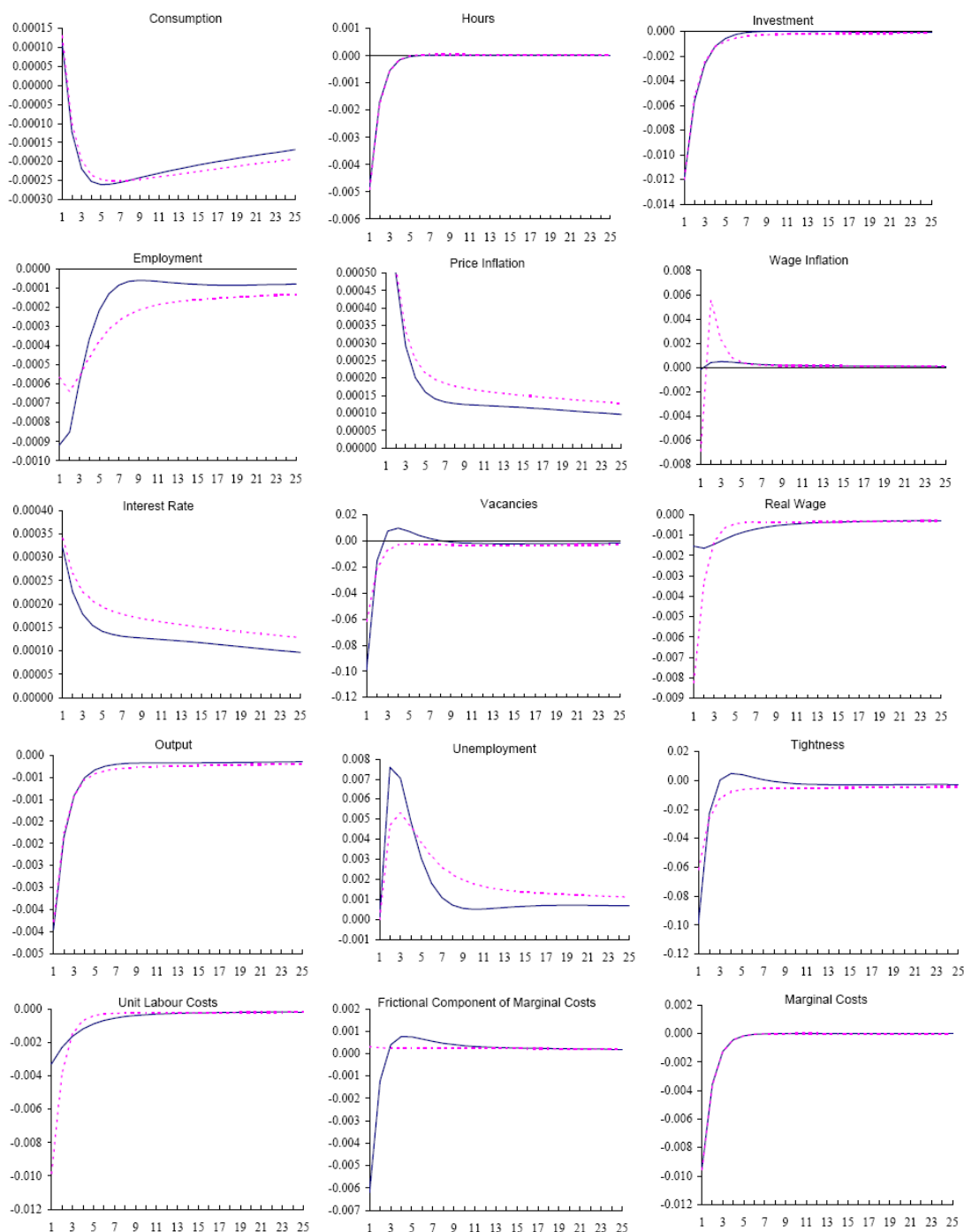
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages.
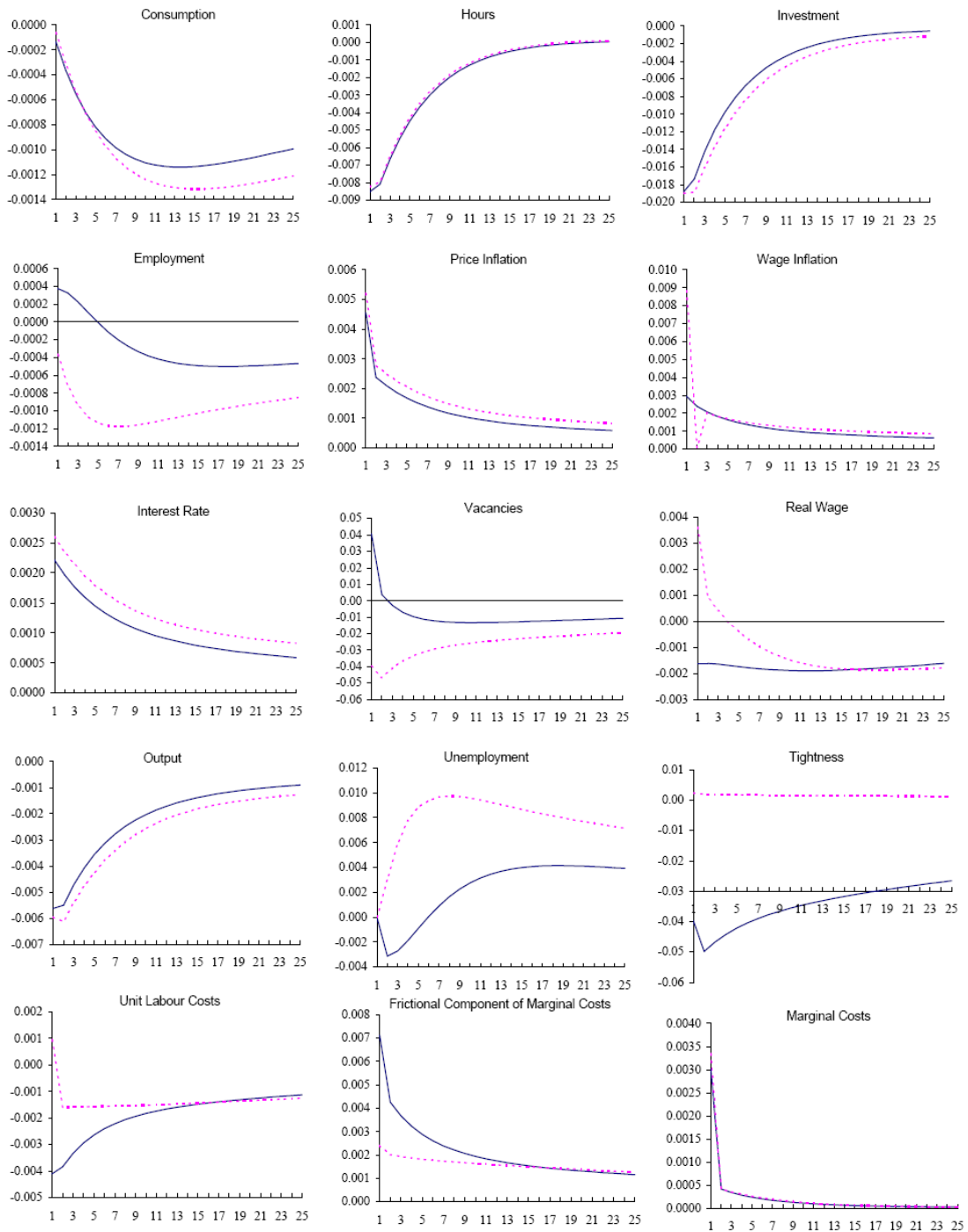
Figure 2: Impulse responses to a neutral technology shock
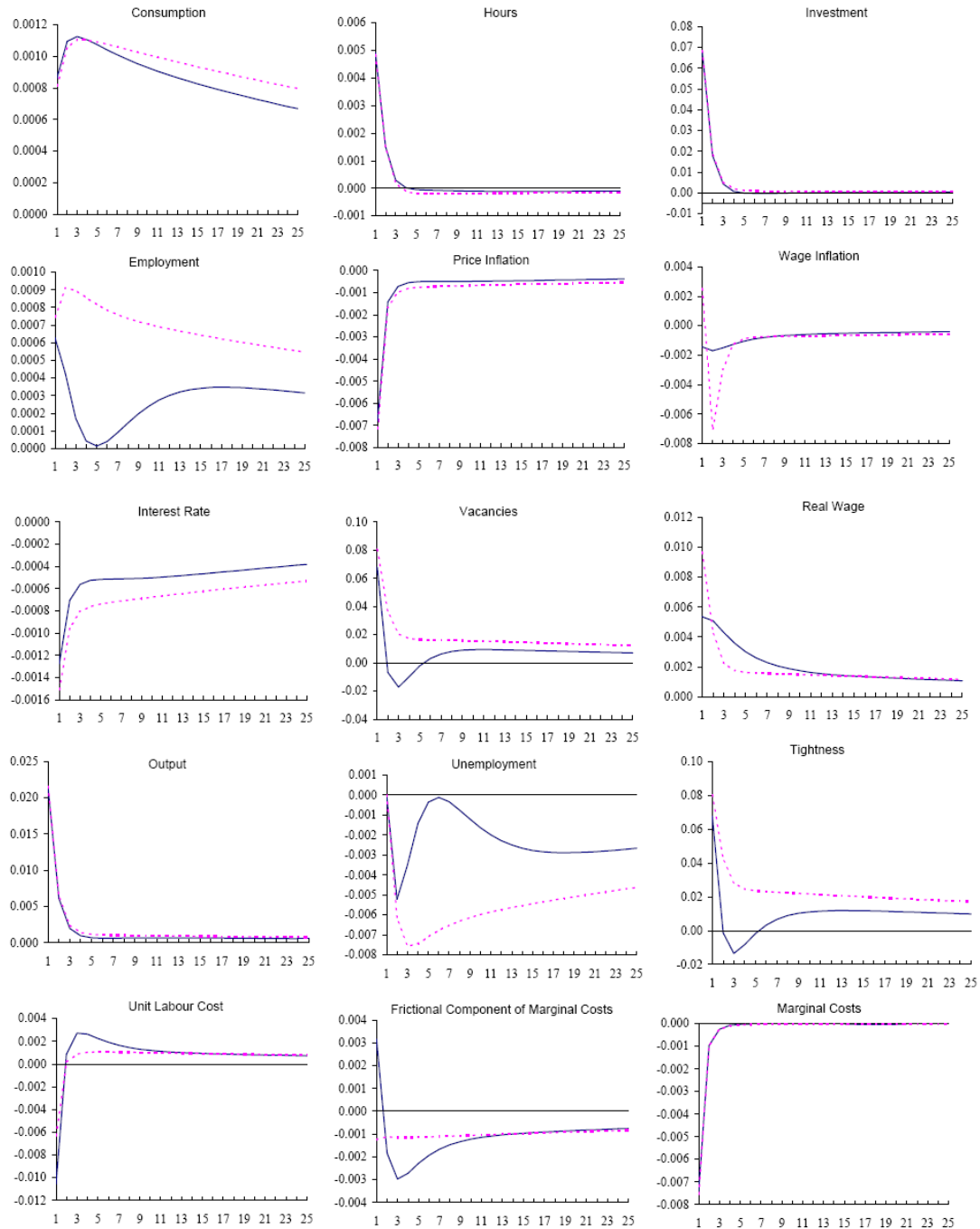
Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages.
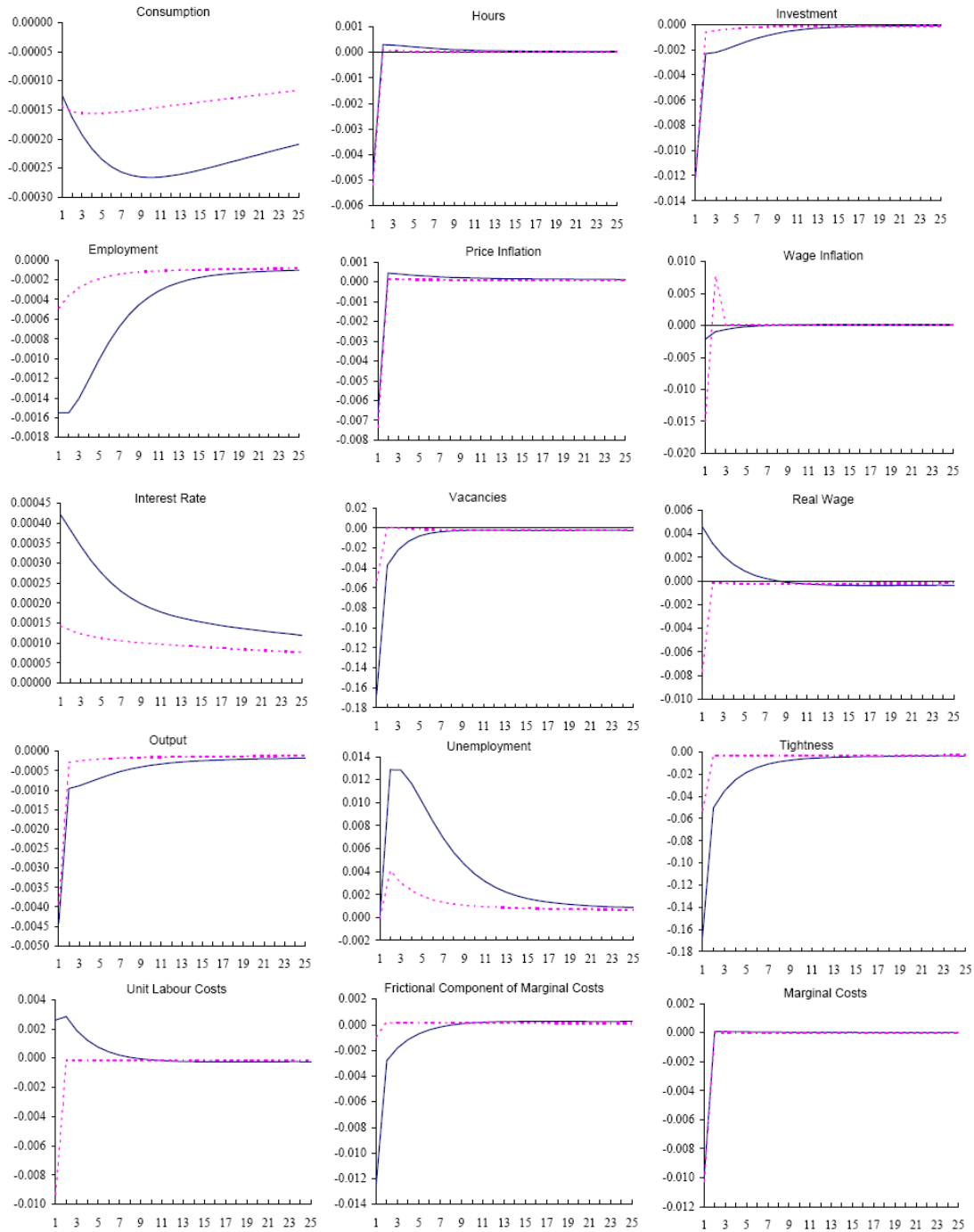
Figure 3: Impulse responses to a labour supply shock

Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages.
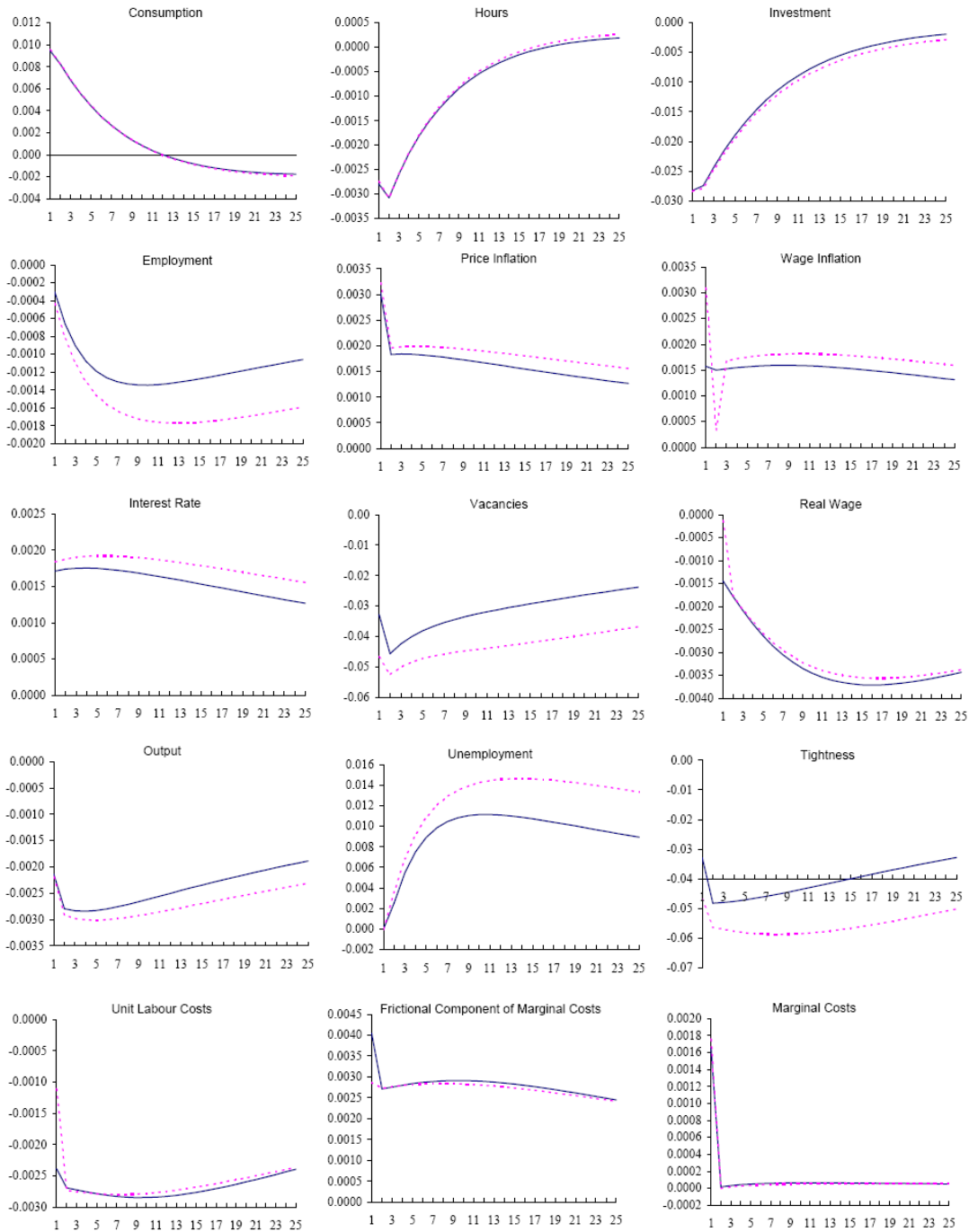
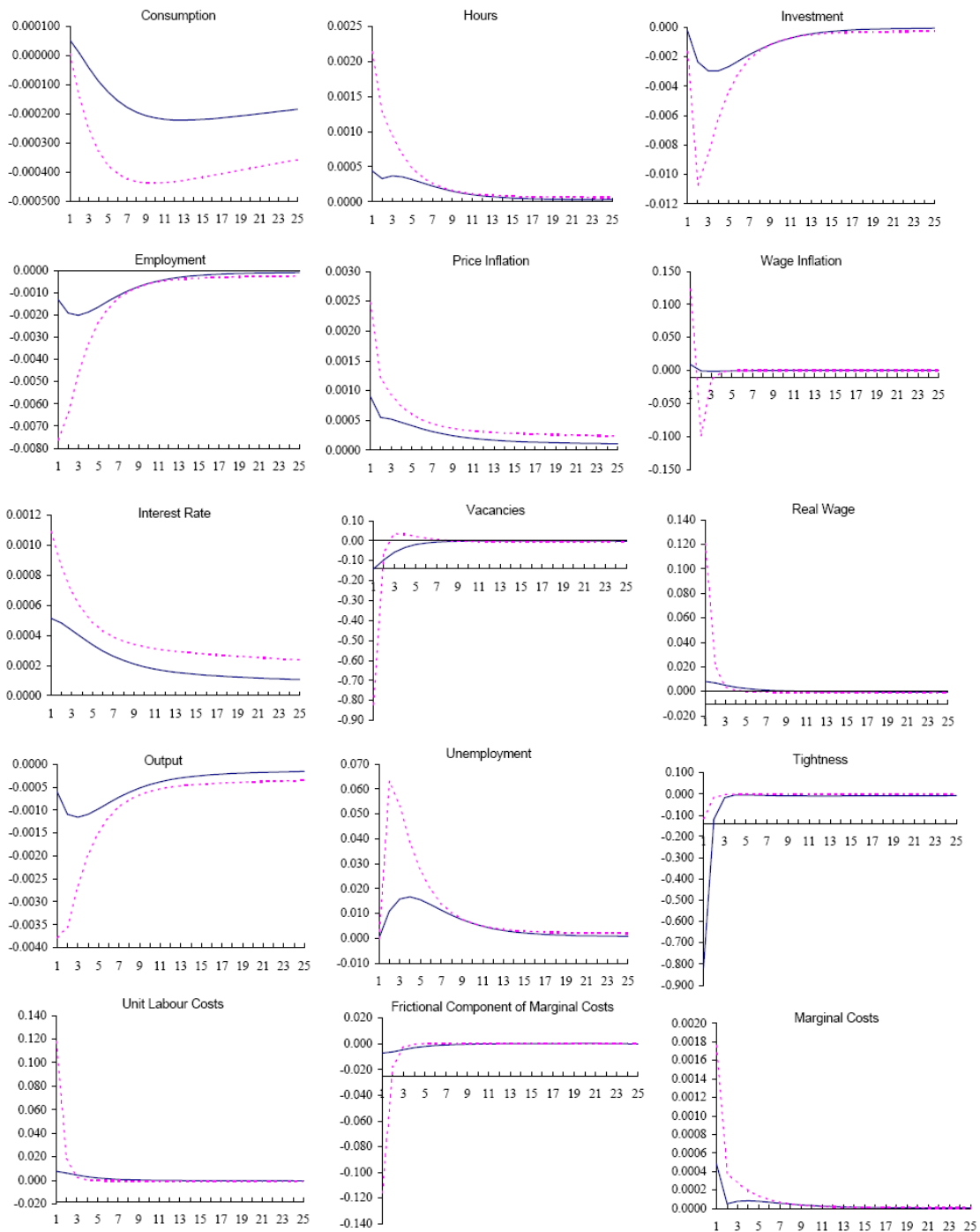# Figure 4: Impulse responses to a monetary policy shock

Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages.

Figure 5: 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.
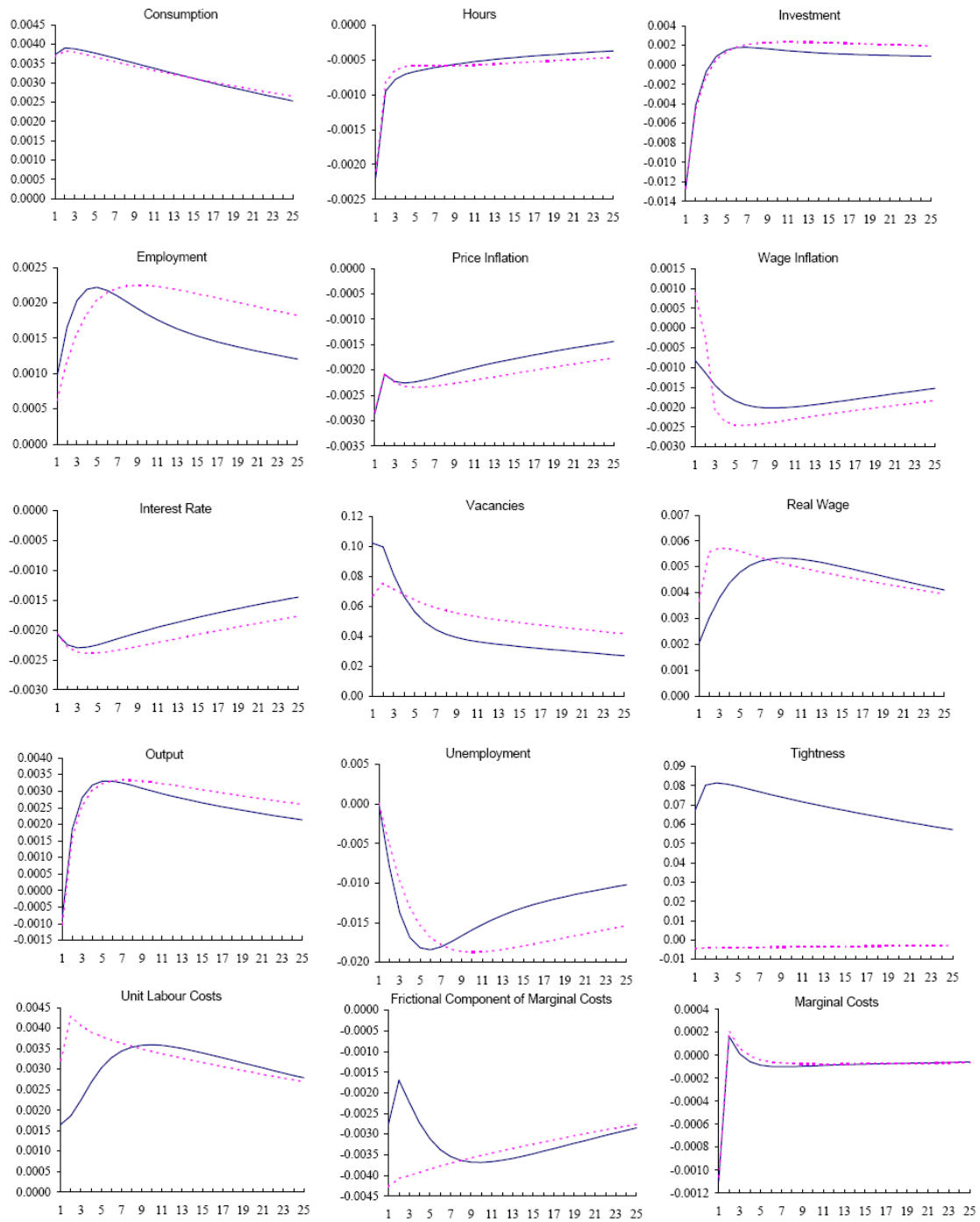
Figure 6: Impulse responses to a bargaining power shock

Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages.
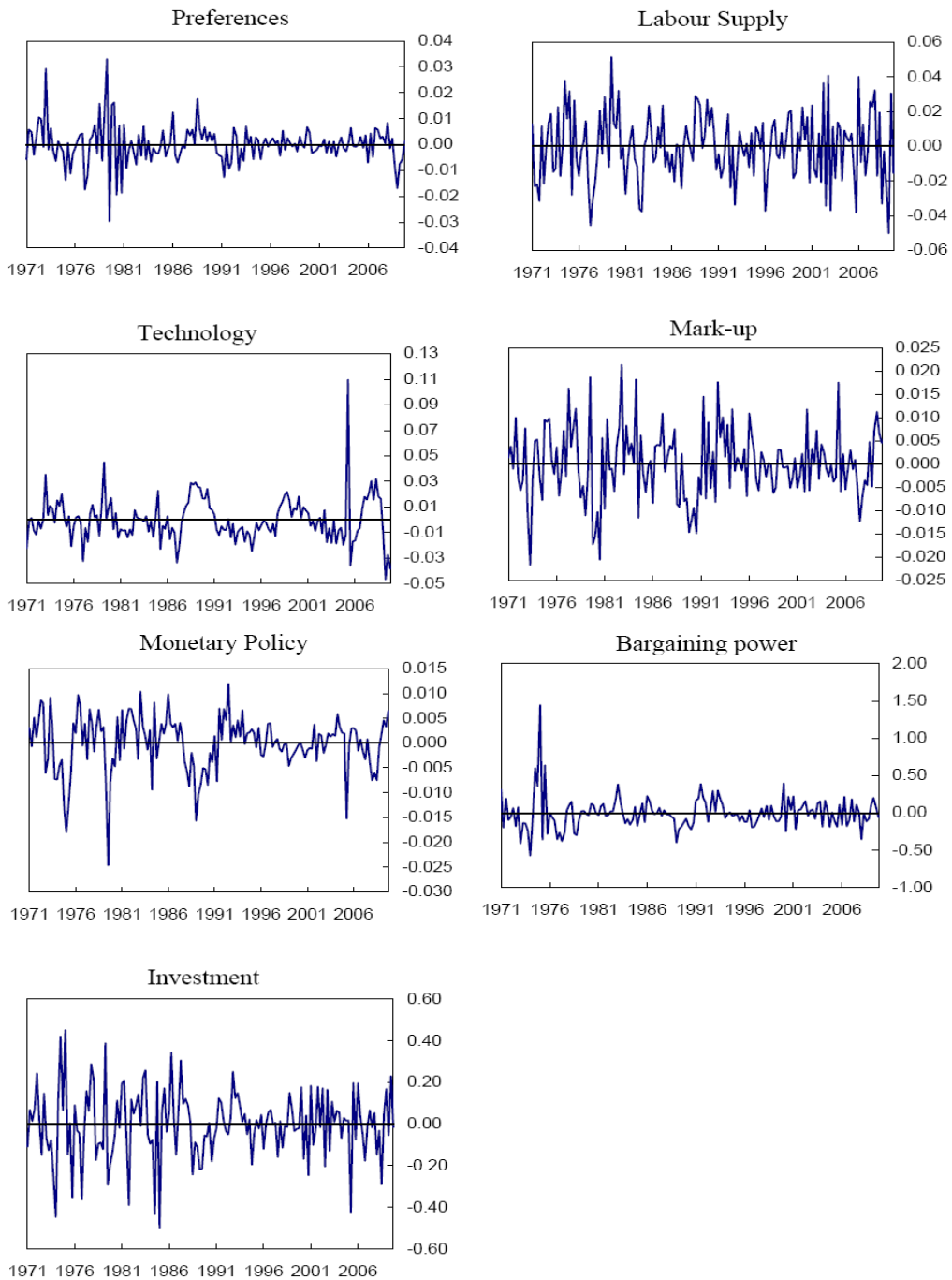
Figure 7: Impulse responses to an investment-specific technology shock

Notes: Solid lines denote the baseline economy with sticky wages. Dashed lines refer to the economy with flexible wages.

Figure 8: Smoothed shocks

References

Andolfatto, D (1996), 'Business cycles and labour market search', *American Economic Review,* Vol. 86, pages 112-32.

Bean, C R (1994), 'European unemployment: a survey', *Journal of Economic Literature*, Vol. 32, pages 573-619.

Bell, B and Smith, J (2002), 'On gross worker flows in the United Kingdom: evidence from the Labour Force Survey', *Bank of England Working Paper No. 160*.

Benati, L (2007), 'The Great Moderation in the United Kingdom', *Journal of Money, Credit and Banking*, Vol. 39(1), pages 121-47.

Bianchi, F, Mumtaz, H and Surico, P (2009), 'The Great Moderation of the term structure of UK interest rates', *Journal of Monetary Economics*, Vol. 56(6), pages 749-906.

Blanchard, O J and Gali, J (2010), 'Labor markets and monetary policy: a New Keynesian model with unemployment', *American Economic Journal: Macroeconomics*, Vol. 2, pages 1-30.

Britton, E, Larsen, J D J and Small, I (2000), 'Imperfect competition and the dynamics of mark-ups', *Bank of England Working Paper No. 110*.

Bunn, P and Ellis, C (2009), 'Price-setting behaviour in the United Kingdom: a microdata approach', *Bank of England Quarterly Bulletin,* Vol.49(1), *pages 28-36.*

Calvo, G (1983), 'Staggered contracts in a utility maximizing framework', *Journal of Monetary Economics,* Vol. 12, pages 383-98.

Card, D (1994), 'Intertemporal labor supply: an assessment', in Sims, C (ed), *Advances in Econometrics*, Cambridge University Press.

Christiano, L J, Eichenbaum, M and Evans, C (2005), 'Nominal rigidities and the dynamic effects of a shock to monetary policy', *Journal of Political Economy*, Vol. 105, pages 249-83.

Christoffel, K, Costain, J, de Walque, G, Kuester, K, Linzert, T, Millard, S and Pierrard, O (2009), 'Inflation dynamics with labour market matching: assessing alternative specifications', *Federal Reserve Bank of Philadelphia Working Paper No. 09-6*.

Christoffel, K and Kuester, K (2008), 'Resuscitating the wage channel in models with unemployment fluctuations', *Journal of Monetary Economics*, Vol. 55(5), pages 865-87.

Christoffel, K, Kuester, K and Linzert, T (2009), 'The role of labor markets for euro area monetary policy', *European Economic Review*, forthcoming.

Christoffel, K and Linzert, T (2006), 'The role of real wage rigidity and labor market frictions for unemployment and inflation dynamics', *Discussion Paper Series 1: Economic Studies No.11/2006,* Deutsche Bundesbank, Research Centre.

Costain, J S and Reiter, M (2008), 'Business cycles, unemployment insurance, and the calibration of matching models', *Journal of Economic Dynamics and Control*, Vol. 32(4), pages 1,120-55.

Dickens, W T, Goette, L, Groshen, E L, Holden, S, Messina, J, Schweitzer, M E, Turunen, J and Ward, M E (2007), 'How wages change: micro evidence from the international wage flexibility project', *Journal of Economic Perspectives*, Vol. 21(2), pages 195-214.

Gali, J and Gertler, M (1999), 'Inflation dynamics: a structural econometric analysis', *Journal of Monetary Economics,* Vol. 44, pages 195-222.

Gertler, M, Sala, L and Trigari, A (2008), 'An estimated monetary DSGE model with unemployment and staggered nominal wage bargaining', *Journal of Money, Credit and Banking*, Vol. 40(8), pages 1,713-64.

Gertler, M and Trigari, A (2009), 'Unemployment fluctuations with staggered Nash bargaining', *Journal of Political Economy*, Vol. 117(1), pages 38-86.

Hagedorn, M and Manovskii, I (2008), 'The cyclical behaviour of equilibrium unemployment and vacancies revisited', *American Economic Review*, Vol. 98(4), pages 1,692-706.

Harrison, R and Oomen, O (2009), 'Evaluating and estimating a DSGE model for the United Kingdom', *Bank of England Working Paper No. 380*.

Hobijn, B and Sahin, A (2007), 'Job-finding and separation rates in the OECD', *Federal Reserve Bank of New York Staff Report 298*.

Krause, M, Lopez-Salido, D J and Lubik, T A (2008a), 'Inflation dynamics with search frictions: a structural econometric analysis', *Journal of Monetary Economics*, Vol. 55(5), pages 892-916.

Krause, M, Lopez-Salido, D J and Lubik, T A (2008b), 'Do search frictions matter for inflation dynamics?', *European Economic Review*, Vol. 52(8), pages 1,464-79.

Krause, M and Lubik, T A (2007), 'The irrelevance of real wage rigidity in the New Keynesian model with search frictions', *Journal of Monetary Economics*, Vol. 54, pages 706-27.

Mattesini, F and Rossi, L (2008), 'Optimal monetary policy in economies with dual labor markets', *Journal of Economic Dynamics and Control*, Vol. 33(7), pages 1,469-89.

Merz, M (1995), 'Search in the labor market and the real business cycle', *Journal of Monetary Economics*, Vol. 36, pages 269-300.

Nickell, S (1997), 'Unemployment and labor market rigidities: Europe versus North America', *Journal of Economic Perspectives*, Vol. 11(3), pages 55-74.

Petrongolo, B and Pissarides, C A (2001), 'Looking into the black box: a survey of the matching function', *Journal of Economic Literature*, Vol. 39(2), pages 390-431.

Ravenna, F and Walsh, C E (2008), 'Vacancies, unemployment, and the Phillips curve', *European Economic Review*, Vol. 52(8), pages 1,494-521.

Smets, F and Wouters, R (2003), 'An estimated dynamic stochastic general equilibrium model of the euro area', *Journal of the European Economic Association*, Vol. 1(5), pages 527-49.

Smets, F and Wouters, R (2007), 'Shocks and frictions in US business cycles: a Bayesian DSGE approach', *American Economic Review*, Vol. 97(3), pages 586-606.

Thomas, C (2008), 'Search and matching frictions and optimal monetary policy', *Journal of Monetary Economics*, Vol. 55, pages 936-56.

Trigari, A (2006), 'The role of search frictions and bargaining for inflation dynamics', *Working Paper No. 304,* IGIER (Innocenzo Gasparini Institute for Economic Research), Bocconi University.

Zanetti, F (2007), 'A non-Walrasian labor market in a monetary model of the business cycle', *Journal of Economic Dynamics and Control*, Vol. 31(7), July, pages 2,413-37.

Zanetti, F (2010), 'Labor market institutions and aggregate fluctuations in a search and matching model', *European Economic Review,* forthcoming.