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Assessing the empirical relevance of labor frictions to business cycle fluctuations

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Abstract

This paper describes a DSGE model augmented with labor frictions, namely: indivisible labor, predetermined employment and adjustment costs. This improves the fit to the data as shown by a higher log marginal likelihood and closer match to key business cycle statistics. The labor frictions introduced are relevant for model dynamics and economic policy: the effect of TFP shocks on most macroeconomic variables is substantially mitigated; fiscal policy leads to a greater crowding out of private sector activity and monetary policy has a lower impact on output. Labor frictions also provide a better match to impulse response functions from VAR models.

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1 Introduction

The understanding of the role of labor markets to business cycle dynamics has for long been viewed as a key question in macroeconomics. Keynes (1936) argued that a failure of the labor market to clear was essential to the understanding of the Great Depression in the 1930s. Labor markets was also at the core of Friedman's (1968) work which identified informational problems as preventing labor markets from clearing at the natural rate of unemployment. This proved to be invaluable to making sense of the emergence of stagflation in the 1970s.

Despite this, for the most part, labor market rigidities have deserved relative little attention by modern researchers working in dynamic stochastic general equilibrium (DSGE) models for the purpose of the analysis of inflation and output cyclical fluctuations. Also, those labor rigidities which have been most recently explored in the literature imply a departure from Walrasian markets. These include search and matching frictions of workers to jobs (Walsh, 2005, and Trigari, 2009), efficiency wages (Alexopoulos, 2004, Danthine and Kurmann, 2004), imperfect competition in labor supply (Zanetti, 2007) and wage stickiness (Erceg, Henderson and Levin, 2000). Of these only imperfect competition in labor supply and wage stickiness have become widely adopted by DSGE researchers, being present in several of the most commonly used references such as Smets and Wouters (2003, 2007) and Christiano, Eichenbaum and Evans (2005). While search and matching frictions have certainly proved insightful in the analysis of labor market flows (see for example Yashiv, 2006) its importance to improving the fit of DSGE models to the aggregate time series data still remains to be proven (see Shimer, 2005, Krause and Lubik, 2007, Krause, Lopez-Salido and Lubik, 2008, and Lubik, 2009).

In this paper I introduce labor frictions which do not imply a departure from Walrasian labor markets into an otherwise standard New Keynesian (NK) model similar to Smets and Wouters (2007).[1] In particular, I assume labor to be indivisible (labor cannot be supplied in

[1] The Smets and Wouters (2007) model includes most real rigidities known to be empirically relevant for DSGE models. Firm specific production factors, as in Woodford (2005), are among the few frictions absent from the model. For an empirical assessment of firm specific employment see Madeira (2014) and for firm specific capital see Madeira (2015).

continuous units, households are constrained to be either in a straight time shift, a straight time and overtime shift or unemployed), predetermined straight time employment numbers (in which case, firms adjust overtime employment to respond to unexpected shocks) and convex labor adjustment costs. Therefore, similarly to Blanchard and Galí (2010), the model allows for unemployment, has elements common to those found in search and match models (which typically also assume indivisible labor and predetermined employment), but abstracts from other less essential ingredients (for example, vacancies are filled immediately which is not the case in standard formulations of search and match models).

The labor rigidities introduced are motivated by empirical evidence and legislation requirements: 1) Studies summarized in Hamermesh (1993), show that the lag in adjusting employment demand to be three to 6 months and that hours per worker adjust more rapidly than employment (Elsby, Hobijn and Sahin, 2010, show that the pattern of a quicker adjustment in hours relative to employment also occurred in the 2007 recession);[2] 2) Empirical studies at the micro level indicate that labor adjustment costs are quite significant (see Hamermesh and Pfann, 1996), with some suggesting they amount to as much as one year payroll for the average worker (notice that this excludes costs which are harder to measure, such as disruptions to production from changing the number of employees); 3) The Fair Labor Standards Act (FLSA) overtime pay provisions cover more than 80% of workers and overall compliance rates are around 90% (see Trejo, 1991).[3]

The model is estimated with Bayesian methods (as in Smets and Wouters, 2007, and Gertler, Sala and Trigari, 2008) which has become the most popular approach in macroeconometrics (see Fernández-Villaverde, 2009). This approach is based on the likelihood which uses all the information in a sample and provides a useful tool for model compari-

[2]Furthermore, Hansen and Sargent (1988) using a vector autoregressive (VAR) approach find that overtime employment appears to adjust more rapidly than full time employment to output innovations. This indicates that many firms are likely to be constrained in the short run in adjusting their total employment and resort to overtime work in order to respond to unexpected fluctuations. Other recent VAR studies confirm that employment and unemployment respond little (if at all) on impact to demand shocks (see Monacelli et al., 2010, Brueckner and Pappa, 2012).

[3]As noted by Trejo (1991), it is surprising how little attention is given to overtime pay by economists. Only 11% of workers earn the minimum wage or below, whereas about 25% of all employees work overtime during a typical week (a fraction that has remained quite stable, see the references in Trejo, 1993).

son that embodies a strong preference for parsimonious modelling (that is, it discriminates against models with more parameters, see Fernández-Villaverde and Rubio-Ramírez, 2004). The estimation uses data on output, consumption, investment, interest rates, straight time employment, overtime employment, inflation and real wages.

Estimation results show that the combination of indivisible labor and adjustment costs leads to a significant improvement in the fit to the data (as shown by a substantially higher log marginal likelihood). The results also shown that the introduction of labor frictions allows the DSGE model to better fit the volatility, contemporaneous correlation with real output growth and first order autocorrelation of key macro variables.

The labor frictions introduced affect the model's dynamics considerably. The effects of total factor productivity (TFP) shocks on several macroeconomic variables is substantially reduced due to costly adjustment of labor. The labor frictions considered also have important considerations for policy makers. Expansionary fiscal policy is shown to have greater negative effects for consumption and investment. Monetary policy is found to have smaller estimated effects on output and hours worked when labor frictions are taken into account. It is also shown that labor frictions allow the DSGE model to match better the impulse response functions estimated with vector autoregressive (VAR) techniques. Moreover, variance decomposition analysis shows that monetary policy shocks account for most fluctuations at business cycle frequencies in a DSGE model with labor frictions in contrast to what happens in a standard NK model.

Prior studies showed that the labor frictions considered here proved to yield valuable insights in the real business cycle (RBC) literature (see Rogerson, 1988, Hansen and Sargent, 1988, Hall, 1996, Chang, Doh and Schorfheide, 2007, and Jaimovich and Rebelo, 2008). Similar types of features are commonplace (in both RBC and NK theory) in the modelling of capital (time-to-build, variable capital utilization and convex adjustment costs). The results in this paper argue these features need to be extended to labor markets in monetary business cycle models as well (the labor share of output is twice that of capital, making the implications even more relevant). This is likely to lead to a better understanding of labor, inflation and output movements at the short to medium run horizon.

The rest of the paper is organized as follows. The DSGE model is presented in the next section, whereas the estimation results are presented in section 3. The analysis of consequences to business cycle dynamics is made in section 4. The paper concludes in section 5 with a discussion of the main findings.

2 The baseline model

In this section I describe the baseline model which consists of a DSGE model similar to Smets and Wouters (2007) but which is extended to include a wide range of labor frictions: labor is considered indivisible (differentiating between unemployment, straight time and overtime employment - the model therefore allows for adjustment along both the intensive and extensive margin in hours), firms must commit to the number of straight time workers they will employ before observing shocks to the economy (but are able to adjust the number of employees working overtime to respond to unexpected shocks) and firms also face convex adjustment costs in changing the number of straight time workers.

2.1 Final goods producers

The final consumption good, Y_t, is produced by a perfectly competitive representative firm by combining a continuum of intermediate goods ($Y(i), i \in [0,1]$) aggregated as in Kimball (1995). The final good producers maximize profits. Their problem is:

$$\max_{Y_t, Y_t(i)} P_t Y_t - \int_0^1 P_t(i) Y_t(i) di,$$

$$s.t. \; [\int_0^1 V(\frac{Y_t(i)}{Y_t}; \varepsilon_t^p) di] = 1,$$

where P_t and $P_t(i)$ are the price of the final and intermediate goods respectively, and V is a strictly concave and increasing function characterized by $V(1) = 1$. The time-varying mark-up in the goods market ε_t^p is determined by the following stochastic process:

$$\ln \varepsilon_t^p = (1 - \rho_p) \ln \varepsilon^p + \rho_p \ln \varepsilon_{t-1}^p - \mu_p \eta_{t-1}^p + \eta_t^p, \tag{1}$$

where η_t^p is an IID-Normal error term. As in Smets and Wouters (2007) to simplify notation, in what follows I leave out this argument.

Profit maximization leads to the following demand for the i^{th} good:

$$Y_t(i) = Y_t V'^{-1}[\frac{P_t(i)}{P_t} \int_0^1 V'(\frac{Y_t(i)}{Y_t}) \frac{Y_t(i)}{Y_t} di]. \tag{2}$$

2.2 Intermediate good firms

The production function of the i^{th} intermediate good firm is:

$$Y_t(i) = \varepsilon_t^a \gamma^{(1-\alpha)t} K_t^s(i)^\alpha [h_1 N_{1,t}(i)^{1-\alpha} + h_2 N_{2,t}(i)^{1-\alpha}] - \gamma^t \Phi, \tag{3}$$

where $K_t^s(i)$ is capital services used in production, $N_{1,t}(i)$ is the share of agents who work the straight time shift (straight time employment) and $N_{2,t}(i)$ the share of agents who work both shifts (overtime employment) and ε_t^a is total factor productivity. γ represents the labor-augmenting deterministic growth rate in the economy, α is the share of capital, h_1 is the length of the straight time shift, h_2 is the length of the overtime shift and Φ is a fixed cost. It is assumed that ε_t^a follows the process:

$$\ln \varepsilon_t^a = (1 - \rho_a) \ln \varepsilon^a + \rho_a \ln \varepsilon_{t-1}^a + \eta_t^a, \tag{4}$$

with η_t^a representing an independent shock with normal distribution of mean zero and standard deviation σ_a. The firm's labor input is given by:

$$L_t(i) = h_1 N_{1,t}(i) + h_2 N_{2,t}(i). \tag{5}$$

The firm's profit is given by:

$$P_t(i)Y_t(i) - (M_t P_t + W_{1,t}h_1)N_{1,t}(i) - W_{2,t}h_2 N_{2,t}(i) - R_t^k K_t^s(i),$$

where M_t corresponds to the real price per period charged to firms per unit of straight time employment ($N_{1,t}$) by an agency which matches workers with firms on behalf of households, $W_{1,t}$ is the nominal hourly wage of the straight shift and $W_{2,t}$ is the nominal hourly wage of the overtime shift and R_t^k corresponds to the real rental cost for capital services. The first order conditions (FOCs) are:

$$M_t P_t + W_{1,t}h_1 = \Theta_t(i)(1-\alpha)\varepsilon_t^a \gamma^{(1-\alpha)t} K_t^s(i)^\alpha h_1 N_{1,t}(i)^{-\alpha}. \tag{6}$$

$$W_{2,t} = \Theta_t(i)(1-\alpha)\varepsilon_t^a \gamma^{(1-\alpha)t} K_t^s(i)^\alpha N_{2,t}(i)^{-\alpha}, \tag{7}$$

$$R_t^k = \Theta_t(i)\alpha\varepsilon_t^a \gamma^{(1-\alpha)t} K_t^s(i)^{\alpha-1}[h_1 N_{1,t}(i)^{1-\alpha} + h_2 N_{2,t}(i)^{1-\alpha}], \tag{8}$$

where $\Theta_t(i)$ is the Lagrange multiplier associated with the production function and equals marginal cost MC_t which is the same for all firms.

Under Calvo pricing with partial indexation, the optimal price set by the firm that is allowed to re-optimize results from:

$$\begin{aligned} & \max_{\tilde{P}_t(i)} E_t \sum_{s=0}^{\infty} \xi_p^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} \left[\tilde{P}_t(i)(\Pi_{l=1}^s \pi_{t+l-1}^{\iota_p} \pi_*^{1-\iota_p}) - MC_{t+s}\right] Y_{t+s}(i), \\ s.t.\ Y_{t+s}(i) &= Y_{t+s} V'^{-1}\left(\frac{P_t(i) X_{t,s}}{P_{t+s}} \tau_{t+s}\right), \end{aligned}$$

where $1-\xi_p$ is the Calvo probability of being allowed to optimize one's price, ι_p is the degree of indexation to past inflation, $\tilde{P}_t(i)$ is the newly set price, $\pi_t = P_t/P_{t-1}$ is inflation and π_* the steady state value, $\beta(\Xi_{t+s}/\Xi_t)(P_t/P_{t+s})$ is the nominal discount factor for firms (β is the households' subjective discount factor and Ξ_t is the households' Lagrange multiplier associated with the budget constraint), $\tau_t = \int_0^1 V'(\frac{Y_t(i)}{Y_t})\frac{Y_t(i)}{Y_t}di$ and

$$X_{t,s} = \left\{ \begin{array}{c} 1 \; for \; s = 0 \\ (\Pi_{l=1}^{s} \pi_{t+l-1}^{\iota_p} \pi_*^{1-\iota_p}) \quad for \; s = 1, ..., \infty \end{array} \right\}.$$

The FOC is:

$$E_t \sum_{s=0}^{\infty} \xi_p^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} Y_{t+s}(i) \left[X_{t,s}\tilde{P}_t(i) + (X_{t,s}\tilde{P}_t(i) - MC_{t+s}) \frac{1}{V'^{-1}(u_{t+s})} \frac{V'(x_{t+s})}{V''(x_{t+s})} \right] = 0, \quad (9)$$

where $x_t = V'^{-1}(u_t)$ and $u_t = \frac{P_t(i)}{P_t}\tau_t$. The curvature of the Kimball goods market aggregator (ε_p) is given by:

$$A = \frac{1 + \frac{V''(1)}{V'(1)}}{2 + \frac{V'''(1)}{V''(1)}} = \frac{1}{\varepsilon^p \varepsilon_p + 1}.$$

The aggregate price index is given by (notice that all firms will chose the same price $\tilde{P}_t$):

$$P_t = (1 - \xi_p)\tilde{P}_t V'^{-1}(\frac{\tilde{P}_t}{P_t}\tau_t) + \xi_p \pi_{t-1}^{\iota_p} \pi_*^{1-\iota_p} P_{t-1} V'^{-1}(\frac{\pi_{t-1}^{\iota_p} \pi_*^{1-\iota_p} P_{t-1}\tau_t}{P_t}). \quad (10)$$

2.3 Households

Agents derive utility from consumption (C_t) and hours of leisure (H_t). The objective function of agent j is given by:

$$E_t \sum_{s=0}^{\infty} \beta^s \log(C_{t+s}(j) - \lambda F_{t+s}) + v \frac{1}{1-\chi} H_{t+s}^{1-\chi}(j)).$$

with the variable $F_t = C_{t-1}$ representing external habit formation and taken by the agent as exogenous (because it reflects the behavior of others, exemplifying the desire of "catching-up with the Joneses"). λ measures the degree of habit formation, v determines the disutility from labor and χ determines the elasticity of labor supply.

Each agent is endowed with T units of time each period. H_t can take one of three values:

-H if the agent is unemployed;

-$H - t_1$ if the agent is employed but works the straight shift only;

-$H - t_1 - t_2$ if the agent works both the straight and overtime shift.

I employ lotteries to convexify the commodity space. Assume $\pi_{1,t}$ and $\pi_{2,t}$ are the probability of working just the straight time shift and the probability of working both shifts respectively. Hence $1-\pi_{1,t}-\pi_{2,t}$ is the probability of being unemployed. An agent's expected single period utility, after normalizing the agent's time endowment to unity ($h_1 = t_1/T$ and $h_2 = t_2/T$), is then:

$$\begin{aligned}
&\pi_{1,t}[\log(C_t(j) - \lambda F_t) + v\frac{1}{1-\chi}(1-h_1)^{1-\chi}] \\
&+\pi_{2,t}[\log(C_t(j) - \lambda F_t) + v\frac{1}{1-\chi}(1-h_1-h_2)^{1-\chi}] \\
&+(1-\pi_{1,t}-\pi_{2,t})[\log(C_t(j) - \lambda F_t) + v\frac{1}{1-\chi}(1)^{1-\chi}].
\end{aligned}$$

Since capital markets are complete (consumption is the same for all agents), one can then write the representative household's utility function as:

$$E_t \sum_{s=0}^{\infty} \beta^s \log(C_{t+s} - \lambda F_{t+s}) - a_1(N_{1,t+s} - N_{2,t+s}) - a_2 N_{2,t+s} - a_0(1 - N_{1,t+s})],$$

where $a_0 = -v\frac{1}{1-\chi}(1)^{1-\chi}, a_1 = -v\frac{1}{1-\chi}(1-h_1)^{1-\chi}, a_2 = -v\frac{1}{1-\chi}(1-h_1-h_2)^{1-\chi}$, $N_{1,t} = \pi_{1,t} + \pi_{2,t}$ and $N_{2,t} = \pi_{2,t}$. The representative agent maximizes the objective function above subject to the sequence of budget constraints given by

$$P_t(C_t+I_t+a(Z_t)K_{t-1})+E_t\left\{\frac{B_t}{\varepsilon_t^b R_t}\right\}-T_t = B_{t-1}+W_{1,t}^h h_1 N_{1,t}+W_{2,t}^h h_2 N_{2,t}+R_t^k Z_t K_{t-1}+D_t^f+D_t^u+D_t^a, \tag{11}$$

and the capital accumulation equation:

$$K_t = (1-\delta)K_{t-1} + \varepsilon_t^i[1 - S(\frac{I_t}{I_{t-1}})]I_t. \tag{12}$$

I_t represents investment expenditures, Z_t is the degree of capital utilization, K_t is the stock of capital (which becomes productive with a one period delay), B_t is the nominal payoff of of a risk-less one period bond, R_t denotes the gross nominal interest rate, T_t are government transfers, $W_{1,t}^h$ and $W_{2,t}^h$ are the nominal hourly wage rates for respectively the straight shift and overtime shift paid to households, D_t^f denotes firms profits, D_t^u denotes profits distributed by labor unions, and D_t^a denotes profits from an agency which matches workers with firms. The function $S(\cdot)$ is an increasing and convex function, of the usual kind assumed in neoclassical investment theory, which satisfies $S(\gamma) = 0$, $S'(\gamma) = 0$, and $S''(\gamma) = \varphi$, δ is the depreciation rate and φ measures convex investment adjustment costs in a log-linear approximation to the equilibrium dynamics. I assume that $a(Z_t)$ is increasing and convex, capturing the idea that increased capital utilization increases the maintenance cost of capital in terms of investment goods. In the steady state $Z = 1$ and $a(1) = 0$. To solve the model, one needs only the inverse of the elasticity of the capital utilization cost function: $a'(1)/a''(1) = (1-\Psi)/\Psi$.

The terms ε_t^b and ε_t^i represent respectively shocks to the risk premium and the investment-specific technology process. These shocks are assumed to follow a first-order autoregressive process with an IID-Normal error term:

$$\ln \varepsilon_t^b = (1-\rho_b)\ln \varepsilon^b + \rho_b \ln \varepsilon_{t-1}^b + \eta_t^b, \tag{13}$$

$$\ln \varepsilon_t^i = (1-\rho_i)\ln \varepsilon^i + \rho_i \ln \varepsilon_{t-1}^i + \eta_t^i, \tag{14}$$

The resulting first-order conditions (FOCs) are:

$$\Xi_t = (C_t - \lambda C_{t-1})^{-1}, \tag{15}$$

$$\frac{W_{1,t}^h}{P_t} h_1 = \frac{(a_1 - a_0)}{\Xi_t}, \tag{16}$$

$$\frac{W_{2,t}^h}{P_t} h_2 = \frac{(a_2 - a_1)}{\Xi_t}. \tag{17}$$

$$\Xi_t = \beta \varepsilon_t^b R_t E_t(\frac{\Xi_{t+1}}{\pi_{t+1}}) \tag{18}$$

$$\Xi_t = \Xi_t^k \varepsilon_t^i [1 - S_N(\frac{I_t}{I_{t-1}}) - S'(\frac{I_t}{I_{t-1}})\frac{I_t}{I_{t-1}}] + \beta E_t[\Xi_{t+1}^k \varepsilon_{t+1}^i S'(\frac{I_{t+1}}{I_t})(\frac{I_{t+1}}{I_t})^2] \tag{19}$$

$$\Xi_t^k = \beta E_t[\Xi_{t+1}\left(\frac{R_{t+1}^k}{P_{t+1}} Z_{t+1} - a(Z_{t+1})\right) + \Xi_{t+1}^k(1-\delta)], \tag{20}$$

$$\frac{R_t^k}{P_t} = a'(Z_t), \tag{21}$$

where Ξ_t^k is the Lagrange multiplier associated with the capital accumulation constraint. Tobin's Q is $Q_t = \Xi_t^k / \Xi_t$ and equals one in the absence of adjustment costs.

The agency which matches workers with firms on behalf of household's chooses $N_{1,t+1}$ (just like capital, straight time employment becomes productive with a one period delay) to maximize:

$$\sum_{s=0}^{\infty} E_t \beta^s \frac{P_t}{P_{t+s}} \frac{\Xi_{t+s}}{\Xi_t} (M_{t+s} P_{t+s} N_{1,t+s} - P_{t+s} N_{t+s}),$$

subject to:

$$N_t = \gamma^t N(\frac{N_{1,t+1}}{N_{1,t}}) N_{1,t}. \tag{22}$$

The function $N(\cdot)$ is an increasing and convex function, which satisfies $N(1) = \delta_{N1}$, $N'(1) = 1$ and $H''(1) = \varphi_{N_1} = 2 \times \varphi_N$. The parameter δ_{N1} can be interpreted as the exogenous quit rate in employment and φ_N measures the degree of labor adjustment costs. .

The resulting first-order condition (FOC) is given by:

$$\gamma^t N'(\frac{N_{1,t+1}}{N_{1,t}}) = E_t \beta \frac{\Xi_{t+1}}{\Xi_t}[M_{t+1} + \frac{N_{1,t+2}}{N_{1,t+1}} \gamma^{t+1} N'(\frac{N_{1,t+2}}{N_{1,t+1}}) - \gamma^{t+1} N(\frac{N_{1,t+2}}{N_{1,t+1}})]. \qquad (23)$$

It is important to discuss briefly the costs involved in the decisions regarding straight time employment and overtime employment. Straight time employment is subject to convex adjustment costs and must be decided before costs to the economy are known. It might appear then that agents would favor adjusting only overtime employment over the business cycle. However, such an interpretation would be wrong because overtime hours are paid at a "premium". This can be seen by combining (16) and (17) to obtain:

$$\frac{W^h_{2,t}}{W^h_{1,t}} = \frac{h_1}{h_2} \frac{(a_2 - a_1)}{(a_1 - a_0)}.$$

Therefore the wage rate for the overtime employment shift is a constant proportion of the wage rate for straight time employment. The exact value of the overtime premium implied by the model depends on the choice of parameter values. One obtains that the overtime wage is about 41% higher than the straight time wage by setting $H = 1369$ (which implies agents have 15 available hours per day for work and leisure), $t_1 = 516$ (which implies a 40 hour per week straight time shift), $t_2 = 155$ (the quarterly mean of overtime hours, for details see Madeira, 2014) and $v = \chi = 1$ as is conventional in most macro models. The model therefore can easily match a value close to the FLSA requirement that overtime wage be time and a half the straight time wage (see Trejo, 1991).

2.4 Intermediate labor union sector

Households supply their homogenous labor to an intermediate labor union which differentiates the labor services and has market power. Unions offer those services to intermediate labor packers. The labor packers maximize (with $d \in \{1,2\}$):

$$\max_{N_{d,t},N_{d,t}(j)} W_{d,t}N_{d,t} - \int_0^1 W_{d,t}(j)N_{d,t}(j)dj,$$
$$s.t.\ [\int_0^1 V^w(\frac{N_{d,t}(j)}{N_{d,t}};\varepsilon_t^w)dj] = 1,$$

where $W_{d,t}$ and $W_{d,t}(j)$ are the price of the composite and intermediate labor services respectively, and V^w an aggregator function as in Kimball (1995) which is a strictly concave and increasing function characterized by $V^w(1) = 1$. The time-varying mark-up in the labor market ε_t^w is assumed to follow the stochastic process below:

$$\ln \varepsilon_t^w = (1-\rho_w)\ln \varepsilon^w + \rho_w \ln \varepsilon_{t-1}^w - \mu_w \eta_{t-1}^w + \eta_t^w, \tag{24}$$

where η_t^w is an IID-Normal error term. As in Smets and Wouters (2007) to simplify notation, in what follows I leave out this argument.

Combining FOCs results in:

$$N_{d,t}(j) = N_{d,t}V^{w\prime-1}[\frac{W_{d,t}(j)}{W_{d,t}}\int_0^1 V^{w\prime}(\frac{N_{d,t}(j)}{N_{d,t}})\frac{N_{d,t}(j)}{N_{d,t}}dj]. \tag{25}$$

Unions set nominal wages in staggered contracts. In particular, a constant fraction $(1-\xi_w)$ of wage contracts is renegotiated in each period. Wages which are not re-optimized are assumed to be indexed to a weighted average of steady state and lagged inflation. Unions take into account the real wage desired by households given in (A13) and (A14) and labor demand. The union chooses $\tilde{W}_{d,t}(j)$, with $d \in \{1,2\}$, to maximize:

$$\max_{\tilde{W}_{d,t}(j)} E_t \sum_{s=0}^{\infty} \xi_w^s \frac{\beta^s \Xi_{t+s}P_t}{\Xi_t P_{t+s}} \left[\tilde{W}_{d,t}(j)h_d(\Pi_{l=1}^s \pi_{t+l-1}^{\iota_w}\pi_*^{1-\iota_w}) - W_{d,t}^h h_d\right] N_{d,t+s}(j),$$
$$s.t.\ N_{d,t+s}(j) = N_{d,t+s}V^{w\prime-1}\left(\frac{W_{d,t+s}(j)X_{t,s}^w}{W_{d,t+s}}\tau_{d,t+s}^w\right)$$

where ι_w is the degree of indexation to past inflation, $\tau_{d,t}^w = \int_0^1 V^{w\prime}(\frac{N_{d,t}(j)}{N_{d,t}})\frac{N_{d,t}(j)}{N_{d,t}}dj$ and:

$$X_{t,s}^w = \left\{ \begin{array}{c} 1 \ for \ s=0 \\ (\Pi_{l=1}^s \pi_{t+l-1}^{\iota_w} \pi_*^{1-\iota_w}) \quad for \ s = 1, ..., \infty \end{array} \right\}.$$

The FOCs are given by:

$$E_t \sum_{s=0}^{\infty} \xi_w^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} N_{d,t+s}(j) \left[X_{t,s}^w \tilde{W}_{d,t}(j) + (X_{t,s}^w \tilde{W}_{d,t}(j) - W_{d,t+s}^h) \frac{1}{V^{w\prime -1}(u_{d,t+s}^w)} \frac{V^{w\prime}(x_{d,t+s}^w)}{V^{w\prime\prime}(x_{d,t+s}^w)} \right] = 0, \tag{26}$$

where $x_{d,t}^w = V^{w\prime -1}(u_{d,t}^w)$ and $u_{d,t}^w = \frac{W_{d,t}(j)}{W_{d,t}} \tau_{d,t}^w$. The markup of the aggregate wage over the wage received by the households is distributed to the households in the form of dividends. The curvature of the Kimball aggregator (ε_w) is given by:

$$A^w = \frac{1 + \frac{V^{w\prime\prime}(1)}{V^{w\prime}(1)}}{2 + \frac{V^{w\prime\prime\prime}(1)}{V^{w\prime\prime}(1)}} = \frac{1}{\varepsilon^w \varepsilon_w + 1}.$$

The aggregate wage indexes are given by:

$$W_{d,t} = (1 - \xi_w) \tilde{W}_{d,t} V^{w\prime -1}(\frac{\tilde{W}_{d,t} \tau_{d,t}^w}{W_{d,t}}) + \xi_w \pi_{t-1}^{\iota_w} \pi_*^{1-\iota_w} W_{d,t-1} V^{w\prime -1}(\frac{\pi_{t-1}^{\iota_w} \pi_*^{1-\iota_w} W_{d,t-1} \tau_{d,t}^w}{W_{d,t}}). \tag{27}$$

2.5 Government policies and market clearing

The model is closed by assuming the central bank follows an interest rate rule according to:

$$\frac{R_t}{R_*} = (\frac{R_{t-1}}{R_*})^{\rho} [(\frac{\pi_t}{\pi_t^*})^{r_\pi} (\frac{Y_t}{Y_t^p})^{r_y}] (\frac{Y_t / Y_{t-1}}{Y_t^p / Y_{t-1}^p})^{r_{\Delta y}} \varepsilon_t^r, \tag{28}$$

where Y_t^p is potential output (defined as the output that would occurs with flexible prices and wages and no "mark-up" shocks), π_t^* is a shock to the inflation objective and ε_t^r is a temporary shock to the interest rate. The parameter R_* is the steady state nominal rate (gross rate), ρ measures the degree of interest rate smoothing, r_π and r_y are respectively the weights on deviations from target inflation and potential output (that is, the "output gap"). There is also a short-run feedback from the change in deviations from potential output determined by $r_{\Delta y}$. The monetary policy shocks follow a first-order autoregressive process with an IID-Normal error term:

$$\ln \pi_t^* = (1-\rho_\pi) \ln \pi^* + \rho_\pi \ln \pi_{t-1}^* + \eta_t^\pi, \tag{29}$$

$$\ln \varepsilon_t^r = (1-\rho_r) \ln \varepsilon^r + \rho_r \ln \varepsilon_{t-1}^r + \eta_t^r. \tag{30}$$

The government budget constraint is given by:

$$P_t G_t + B_{t-1} = T_t + \frac{B_t}{R_t}, \tag{31}$$

where G_t represents government spending which when expressed relative to the steady state output path is denoted as ε_t^g and follows the exogenous process shown below:

$$\ln \varepsilon_t^g = (1-\rho_g) \ln \varepsilon^g + \rho_g \ln \varepsilon_{t-1}^g + \eta_t^g + \rho_{ga} \eta_t^a, \tag{32}$$

where η_t^g is an IID-Normal error term.

Finally, the aggregate economy's resource constraint is:

$$Y_t = C_t + I_t + G_t + a(Z_t) K_{t-1} + N_t. \tag{33}$$

3 Model Estimation

3.1 Estimation Methodology

I adopt a Bayesian estimation methodology similar to that of Smets and Wouters (2007). The log posterior function (which combines the likelihood of the data with priors on the model's parameters) is maximized to yield estimates of the mode and standard deviation.

The Metropolis-Hastings algorithm is then used to obtain estimates of the mean of the posterior distribution.

The dataset used consists of the following seasonally adjusted quarterly US aggregate time series: 100 times the log difference of the GDP deflator (dlP_t), real consumption ($dlCONS_t$), real investment ($dlINV_t$), real wages ($dlWAG_t$) and real GDP ($dlGDP_t$), the fraction of the civilian noninstitutional population employed in nonagriculture industries at work 35 hours and over a week ($N1_t$), the fraction of the civilian noninstitutional population employed in nonagriculture industries at work 41 hours and over a week ($N2_t$), and the federal funds rate ($FEDFUNDS_t$).

The estimation is done for the period 1984Q1 to 2007Q4. The reason for this is that the Bureau of Labor Statistics (BLS) only collects data on $N1_t$ and $N2_t$ since 1976Q3. The decision to start estimation in 1984Q1 was done to avoid any issues arising from potential structural breaks in monetary policy in the late 70s or early 80s. The sample period ends in 2007Q4 in order to avoid any potential estimation bias from nonlinearity associated with the zero lower bound period.

The corresponding measurement equations are:

$$\begin{bmatrix} dlGDP_t \\ dlCONS_t \\ dlINV_t \\ dlWAG_t \\ N1_t \\ N2_t \\ dlP_t \\ FEDFUNDS_t \end{bmatrix} = \begin{bmatrix} \bar{\gamma} \\ \bar{\gamma} \\ \bar{\gamma} \\ \bar{\gamma} \\ \bar{n}_1 \\ \bar{n}_2 \\ \overline{\pi} \\ \overline{r} \end{bmatrix} + \begin{bmatrix} \hat{y}_t - \hat{y}_{t-1} \\ \hat{c}_t - \hat{c}_{t-1} \\ \hat{\imath}_t - \hat{\imath}_{t-1} \\ \hat{w}_t - \hat{w}_{t-1} \\ \hat{N}_{1,t} \\ \hat{N}_{2,t} \\ \hat{\pi}_t \\ \hat{R}_t \end{bmatrix}, \tag{34}$$

where l and dl stand respectively for log and log difference, lower case variables represent detrended real variables and hats denote variables in log deviation from the steady state. The parameter $\bar{\gamma} = 100(\gamma - 1)$ is the common quarterly trend growth rate to real GDP, consumption, investment and wages, while $\overline{\pi} = 100(\pi_* - 1)$ and $\overline{r} = 100(R_* - 1)$ are the average values of inflation and interest rate. The parameters $\bar{n}_1$ and $\bar{n}_2$ are the average values of straight time employment and overtime employment, which are normalized to be equal to zero.

3.2 Prior Distribution of the Parameters

The priors for the estimated parameters of the baseline model (Model 1) are similar to Smets and Wouters (2007). To summarize briefly. Some parameters are fixed in the estimation procedure. The depreciation rate δ is fixed at 0.025, the exogenous spending-GDP ratio is set at 18%, the steady state mark-ups in the goods and labor markets (ε^p and ε^w) are set at 1.5, the curvature parameters of the Kimball aggregators in the goods and labor market (ε_p and ε_w) are both set at 10, the steady state quit rate in employment (δ_{N1}) is set at 0.1 (see Shimer, 2005), the straight time shift (h_1) is set at 0.38 and the overtime shift (h_2) at 0.11 (for details see Madeira, 2014). The parameters v and χ are calibrated so that in the steady state straight time employment and overtime employment are equal to 0.42 and 0.15 respectively (the mean values of their respective time series).

The quarterly trend growth rate $\overline{\gamma}$ is assumed to be of mean 0.4 while the annualized steady state inflation and discount rates respective prior means are 2.5% and 1% respectively. For the Taylor rule the mean prior inflation and output gap weights (including the short run reaction coefficient) are assumed have mean 1.5 and 0.125 respectively, which is consistent with observed variations in the Federal Funds rate over the Greenspan era (see Taylor (1999)). The prior distribution on the coefficient on the lagged interest rate is assumed to follow a beta distribution with mean 0.75 which is consistent with the estimates of Clarida, Gali and Gertler (2000).

The remaining prior means of the structural parameters are as follows: the intertemporal elasticity of substitution is set at 1.5, the habit parameter is set at 0.7, the adjustment cost parameter for investment and employment are both set around 4, the capital share is set at 0.3, the capacity utilization elasticity is set at 0.5, finally the Calvo probabilities of prices and wages are assumed to be 0.66 and the degree of indexation of prices and wages assumed to be 0.5.

The standard errors of the shocks are assumed to follow an inverse-gamma distribution with a mean of 0.10. The autoregressive (AR) and moving average (MA) parameters are assumed to be beta distributed with mean 0.5.

The first three columns of tables 1 and 2 give an overview of the assumptions made regarding the prior distribution (shape, mean and standard deviation) of the estimated parameters. In order to assess the empirical relevance of labor frictions, Model 1 will be compared to Model 2 which is identical in every aspect but does not assume predetermined straight time employment and has the employment adjustment cost fixed at only 0.2 (with a value of zero the model would imply that the straight time employment and overtime employment series are identical which is counterfactual) which is 20 times smaller than the prior mean adopted for Model 1.

3.3 Parameter Estimates

For summary purposes I present only the mean and the standard deviation of the posterior distributions for the parameters, a choice also made by Rabanal and Rubio-Ramírez (2005). Parameter estimates for Model 1 and Model 2 are broadly in line with those found in other studies such as Smets and Wouters (2007).

A few parameters do appear to be affected by the introduction of labor frictions and due to space concerns I focus the discussion on those. The estimates of Model 1 for the degree of investment adjustment costs (φ) and the Calvo wage stickiness probability of nonadjustment (ζ_w) are respectively 5.63 and 0.7. In the case of Model 2 the estimates for the same parameters are respectively 7.59 and 0.94. So the omission of relevant labor frictions from DSGE models appears to bias upwards the estimates of these parameters. Another structural parameter which was affected was the capital share, which was estimated at a value of 0.18 in Model 1 and 0.1 in Model 2.

In Model 1 the employment adjustment cost parameter (φ_N) was estimated to be 32.23.

This is substantially higher than the mean prior value of 4 which was quite conservative (chosen to be the same as that of investment adjustment costs). The estimate is quite close to the 33 value adopted as the mean prior for labor adjustment costs by Chang, Doh and Schorfheide (2007). A value of 33 implies that the average recruiting cost is about 50% of a quarterly salary of a worker recruited (which matches the nation-wide average recruiting expenses for new workers in the US, for details see Chang, Doh and Schorfheide, 2007).

With respect to the estimates of the volatility of exogenous shocks the differences are small except for the risk premium (σ_b) and inflation objective (σ_π) shocks. The estimated value of σ_b is 0.21 for Model 1 and only 0.10 for Model 2. The lower volatility of the risk premium shock in Model 2 is compensated by a higher degree of autocorrelation for this same shock (ρ_b estimated at 0.88 in Model 2 but only 0.54 in Model 1) and a higher volatility of the inflation objective shock (σ_π estimated at 0.24 in Model 2 but only 0.11 in Model 1). The MA coefficients of the price and wage mark-up processes are also different between the models. Model 1 has a higher MA price mark-up coefficient (0.83 compared to 0.50 for Model 2) but a lower MA wage mark-up coefficient (0.49 compared to 0.92 for Model 2).

4 Implications for Business Cycle Fluctuations

4.1 Data Fit

I use the marginal likelihood, obtained by modified harmonic mean estimation, to evaluate the overall empirical performance of the models. The values are displayed in the last line of Table 2. The log marginal likelihood is highest for Model 1 (-399.07 with Model 2 having only -527.71). This suggests that labor frictions improve the New Keynesian model's fit to the data. To evaluate how substantial this improvement is I made use of the Kass and Raftery (KR) criterion. Kass and Raftery (1995) propose that values of twice the difference of the log marginal likelihoods of two models above 10 can be considered as very strong evidence in favor of the model with highest log marginal likelihood. Comparing Model 1 with Model 2 yields a KR criterion of 257.28. The KR criterion therefore strongly supports the importance of labor frictions, namely labor adjustment costs, for the understanding of business cycle fluctuations. In Madeira (2013) it is shown that this conclusion is robust to using 100 times the log of average hours worked (for the nonfarm business sector for all persons), $lHOURS_t$, instead of data on straight time employment and overtime employment, as well as numerous modelling changes (such as not including habit formation, price and wage indexation to lagged inflation, having capital adjustment costs instead of investment adjustment costs and several other differences).

I now study the ability of Model 1 and Model 2 (simulated under their respective estimated mean parameter values) to match the following key business cycle statistics for the US aggregate time series data used to estimate the models: volatility (σ), contemporaneous correlation with real output growth ($\rho_{\Delta y}$) and first order autocorrelation (ρ_1). The results are shown in Table 3 which also includes information for $lHOURS_t$ which was not used in the estimation of the models (but is often used for DSGE model estimation). The counterpart for the hours series in the Model 1 and Model 2 is the L_t variable. The results seem to substantially favor Model 1, confirming the value of labor frictions to better understand macroeconomic time series data. Model 1 matches 19 of the 27 US data statistics in Table 3 more closely than Model 2. Model 2 only matches better 5 of the 27 business cycle statistics better than Model 1, which are: the volatility of real wage growth, the volatility of inflation, the volatility of interest rates, the contemporaneous correlation of real wage growth with real output growth and the contemporaneous correlation of average hours worked with real output growth. Model 1 and Model 2 do equally well in matching the volatility of consumption growth, the contemporaneous correlation of real output growth with real output growth (this is one for both models, as would be the case for any DSGE model) and the first order autocorrelation of straight time employment.

4.2 Impulse Response Functions

Due to space constraints only the impulse response functions (IRFs) for the total factor productivity shock (ε_t^a), fiscal policy (ε_t^g) and the temporary interest rate shock (ε_t^r) are shown. The web appendix includes the IRFs of all shocks.

Figure 1 shows that Model 1 and Model 2 differ in their predictions for the estimated mean responses of economic variables to exogenous changes to total factor productivity in a statistically significant way (the 90% confidence interval, hence CI, is shown in the figure). Figure 1 shows that labor frictions imply smaller average responses of most economic variables (output, consumption, interest rates, inflation and straight time employment) to a total factor productivity shock.

The response of employment and hours to technology shocks is the subject of considerable attention in macroeconomics. Galí (1999) using a structural VAR found that both employment and hours decline in response to a positive technology shock. Later research by Mumtaz and Zanetti (2012) also using a structural VAR but with additional restrictions supports an increase in the use of labor in response to neutral technology shocks. In addition, Mumtaz and Zanetti (2015) show that after allowing for time-varying coefficients that the magnitude of the response of labor market variables to technology shocks varies across time. The question of how technology shocks affect labor markets therefore remains unsettled and remains deserving of further investigation.

The intensity of the debate is due to the contradiction between the results of Galí (1999) and the implication of basic RBC models (see for example King and Rebelo, 2000) that positive technology shocks lead to an increase in hours worked. One way to reconcile RBC research with the findings of Galí (1999) is the introduction of search and match in the labor market to RBC models (see Mandelman and Zanetti, 2014). This implies that labor frictions are an important component in determining the response of employment and hours to technology shocks. Therefore it is worth examining how the labor frictions considered in this paper have impacted labor market dynamics with respect to productivity shocks. The IRFs to a positive technology shock of Model 1 in Figure 1 show a negative reaction of hours and overtime employment but a positive reaction of straight time employment. This indicates that hours and employment can have opposite reaction to technology shocks and adds a new dimension to the debate of the business cycle impact on labor markets from technology shocks.

Figure 2 shows the implications for economic variables of Model 1 and Model 2 with respect to fiscal policy. Figure 2 shows that both Model 1 and Model 2 predict a similar response of average hours worked. However, in the case of Model 1 this is accounted by a larger increase in overtime employment relative to Model 2, while the estimated increase in straight time employment of higher government spending is smaller for Model 1 than for Model 2. Figure 2 also shows that labor frictions result in greater crowding out of consumption and investment to fiscal expansion. Wages also fall by more in the case of Model 1 relative to Model 2 in reaction to an increase in government spending. Taking into account labor frictions suggests the benefits of fiscal expansion to be smaller than those in the conventional New Keynesian model while the adverse effects are found to be larger.

Figure 3 shows the IRFs of Model 1 and Model 2 to a temporary 1% interest rate shock. Figure 3 also includes the vector autoregressive (VAR) mean IRFs estimates to monetary policy shocks of Altig, Christiano, Eichenbaum and Linde (2004), hence ACEL. For the sake of better exposition Figure 3 omits the CI of the IRFs of Model 1 and Model 2 (this is however included in a figure shown in the web appendix, which confirms the differences between Model 1 and Model 2 are in fact statistically significant). Figure 3 shows that Model 1 matches better than Model 2 the IRFs obtained by the VAR model of ACEL with respect to most variables (namely, output, consumption, investment, hours and interest rates). Model 2 seems to match the estimates of ACEL more closely with respect to wages. Both Model 1 and Model 2 seem to match the IRFs of the VAR with respect to inflation equally well.

4.3 Variance Decomposition

The contribution of each of shock to the 20 quarter forecast error variance of real output growth, inflation and the nominal interest rate is shown in Table 4.[4] The numbers for Model

[4] As indicated by King and Rebelo (2000) the cyclical component consists mainly of 'those parts of output with periodicities between 6 and 32 quarters', since 20 quarters is approximately the midpoint of this interval, I choose it as the variance decomposition forecast horizon in order to obtain a good characterization of the relevant sources of business cycle fluctuations

1 and Model 2 in Table 4 were obtained using the respective mean parameter estimates shown in tables 1 and 2.

Model 1 and Model 2 differ somewhat in how they account for fluctuations in real output growth. In both models, it is total factor productivity shocks which are the most relevant for fluctuations at the medium frequency. However, Model 1 places higher weight on government spending and investment-specific technology shocks relative to Model 2 which instead places higher weight on risk premium shocks. Both models place substantial weight on monetary policy shocks. But Model 1 places substantial weight on both the temporary shock to the interest rate and the shock to the inflation objective, while Model 2 places most weight on the temporary shock to the interest rate.

Just as with Smets and Wouters (2007), fluctuations in inflation at medium frequency are nearly completely explained by exogenous movements in the mark-up shocks. So labor frictions do not seem to affect substantially the dynamics of inflation. While Model 1 and Model 2 share many similarities with respect to the driving forces of business cycle fluctuations of real output growth and inflation, the same does not occur with respect to the interest rate.

In Smets and Wouters (2007) monetary policy shocks account for most interest rate fluctuations at the short horizons (one and two quarters) but for only about 20% of fluctuations at medium horizons (10 and 40 quarters). This is consistent with what was obtained for Model 2 with the two monetary policy shocks accounting for 26.95%. However, the introduction of labor frictions changes this dramatically. In Model 1 it is shown that when labor frictions are included that monetary policy shocks can account for most fluctuations in the nominal interest rate (with the two shocks adding up to a total of 71.89%) at a 20 quarter horizon.

5 Conclusion

This paper presents a New Keynesian model with a wide range of labor frictions: indivisible labor, predetermined straight time employment numbers and labor adjustment costs. This combination is proven to lead to significant improvements of the log marginal likelihood and in the matching of key business cycle moments. Labor frictions affect the model's dynamics substantially. Costly labor adjustment mitigates the reaction of most economic variables to total factor productivity shocks. Fiscal policy is shown to imply a greater crowding out of consumption and investment expenses under models with labor frictions. This suggests that an important topic for future research is to examine the consequences of labor frictions to fiscal multipliers at the zero lower bound. The introduction of labor frictions also enables the New Keynesian model to better match the estimated reaction to monetary policy shocks obtained from VAR models. Finally, a variance decomposition analysis implies that when labor frictions are taken into account that monetary policy shocks account for most fluctuations at business cycle frequencies.

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6 Tables

Table 1: Bayesian Estimation of Structural Parameters

	Prior Distribution			Estimated Maximum Posterior			
				Model 1		Model 2	
	Type	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
$\bar{n}_1$	Normal	0.00	2.00	-2.34	1.27	-2.83	1.67
$\bar{n}_2$	Normal	0.00	2.00	0.93	1.88	0.18	2.00
$\bar{\gamma}$	Normal	0.40	0.10	0.45	0.02	0.44	0.01
$100(\beta^{-1}-1)$	Gamma	0.25	0.10	0.27	0.07	0.26	0.08
$\overline{\pi}$	Gamma	0.625	0.10	0.56	0.05	0.63	0.08
λ	Beta	0.70	0.10	0.39	0.05	0.31	0.07
Ψ	Beta	0.50	0.15	0.70	0.09	0.72	0.09
φ	Normal	4.00	1.50	5.63	1.29	7.59	1.15
φ_N	Normal	4.00	5.00	32.23	3.18	-	-
α	Normal	0.30	0.05	0.18	0.02	0.10	0.01
ζ_p	Beta	0.66	0.10	0.96	0.01	0.94	0.02
ζ_w	Beta	0.66	0.10	0.70	0.06	0.94	0.04
t_p	Beta	0.50	0.15	0.52	0.12	0.47	0.09
t_w	Beta	0.50	0.15	0.45	0.16	0.48	0.16
ρ	Beta	0.75	0.10	0.80	0.04	0.87	0.05
r_π	Normal	1.500	0.25	1.36	0.22	1.56	0.24
r_y	Normal	0.125	0.05	0.16	0.04	0.11	0.04
$r_{\Delta y}$	Normal	0.125	0.05	0.19	0.04	0.42	0.04

The data covers the period between 1984Q1 to 2007Q4.

Table 2: Bayesian Estimation of Exogenous Shock Parameters

	Prior Distribution			Estimated Maximum Posterior			
				Model 1		Model 2	
	Type	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
σ_a	Inv. Gamma	0.10	2.00	0.34	0.02	0.35	0.03
σ_b	Inv. Gamma	0.10	2.00	0.21	0.03	0.10	0.02
σ_g	Inv. Gamma	0.10	2.00	0.26	0.02	0.20	0.02
σ_i	Inv. Gamma	0.10	2.00	0.40	0.05	0.42	0.05
σ_r	Inv. Gamma	0.10	2.00	0.15	0.01	0.17	0.02
σ_π	Inv. Gamma	0.10	2.00	0.11	0.02	0.24	0.06
σ_p	Inv. Gamma	0.10	2.00	0.13	0.01	0.11	0.01
σ_w	Inv. Gamma	0.10	2.00	0.37	0.04	0.39	0.03
ρ_a	Beta	0.50	0.20	0.97	0.01	0.99	0.01
ρ_b	Beta	0.50	0.20	0.54	0.11	0.88	0.02
ρ_g	Beta	0.50	0.20	0.94	0.01	0.91	0.02
ρ_i	Beta	0.50	0.20	0.55	0.08	0.52	0.06
ρ_r	Beta	0.50	0.20	0.47	0.06	0.41	0.08
ρ_π	Beta	0.50	0.20	0.98	0.01	0.96	0.01
ρ_p	Beta	0.50	0.20	0.54	0.07	0.47	0.09
ρ_w	Beta	0.50	0.20	0.61	0.18	0.88	0.07
μ_p	Beta	0.50	0.20	0.83	0.03	0.50	0.12
μ_w	Beta	0.50	0.20	0.49	0.20	0.92	0.05
ρ_{ga}	Beta	0.50	0.25	0.82	0.09	0.89	0.06
Log data density (modified harmonic mean)				-399.07		-527.71	

The data covers the period between 1984Q1 to 2007Q4.

Table 3: Business Cycle Statistics

	US data			Model 1			Model 2		
	σ	$\rho_{\Delta y}$	ρ_1	σ	$\rho_{\Delta y}$	ρ_1	σ	$\rho_{\Delta y}$	ρ_1
$dlGDP_t$	0.54*	1.00**	0.21*	0.79	1.00	0.23	1.09	1.00	0.15
$dlCONS_t$	0.50**	0.56*	0.07*	0.91	0.76	0.25	0.91	0.78	0.44
$dlINV_t$	1.47*	0.61*	0.52*	1.78	0.61	0.56	1.80	0.30	0.59
$dlWAG_t$	0.72	0.00	0.14*	0.84	0.23	0.18	0.72	0.16	0.03
$lHOURS_t$	2.00*	0.03	0.97*	2.62	0.08	0.99	5.33	0.07	0.99
dlP_t	0.23	-0.14*	0.59*	0.22	-0.07	0.65	0.23	0.02	0.66
$FEDFUNDS_t$	0.59	0.09*	0.98*	0.29	0.02	0.90	0.54	0.41	0.87
$lN1_t$	3.87*	-0.28*	0.80**	3.02	-0.08	0.999	7.29	-0.07	0.999
$lN2_t$	7.56*	-0.02*	0.95*	17.11	0.27	0.97	30.28	0.29	0.99

The data covers the period between 1984Q1 to 2007Q4. * indicates Model 1 does better in matching data. **indicates Model 1 and Model 2 do equally well in matching data. Standard deviation of a variable is denoted by σ, contemporaneous correlation with real output growth is denoted by $\rho_{\Delta y}$, and first order autocorrelations is denoted by ρ_1.

Table 4: Variance Decomposition (in percentage) 20 quarter horizon

	ε_t^a	ε_t^b	ε_t^g	ε_t^i	ε_t^r	π_t^*	ε_t^p	ε_t^w
$dlGDP_t$ (Model 1)	26.67	14.59	11.30	9.77	18.91	17.18	1.26	0.32
dlP_t (Model 1)	0.04	0.00	0.00	0.00	0.01	6.61	93.27	0.06
$FEDFUNDS_t$ (Model 1)	0.46	11.23	0.93	3.65	56.51	15.38	11.01	0.83
$dlGDP_t$ (Model 2)	31.16	21.70	5.88	2.17	27.61	8.67	1.07	1.74
dlP_t (Model 2)	1.91	0.03	0.00	0.01	0.07	8.55	82.54	6.89
$FEDFUNDS_t$ (Model 2)	0.69	65.32	0.97	0.78	4.61	22.34	1.46	3.83

7 Figures

Figure 1: IRFs to a TFP shock (Model 1 and Model 2)

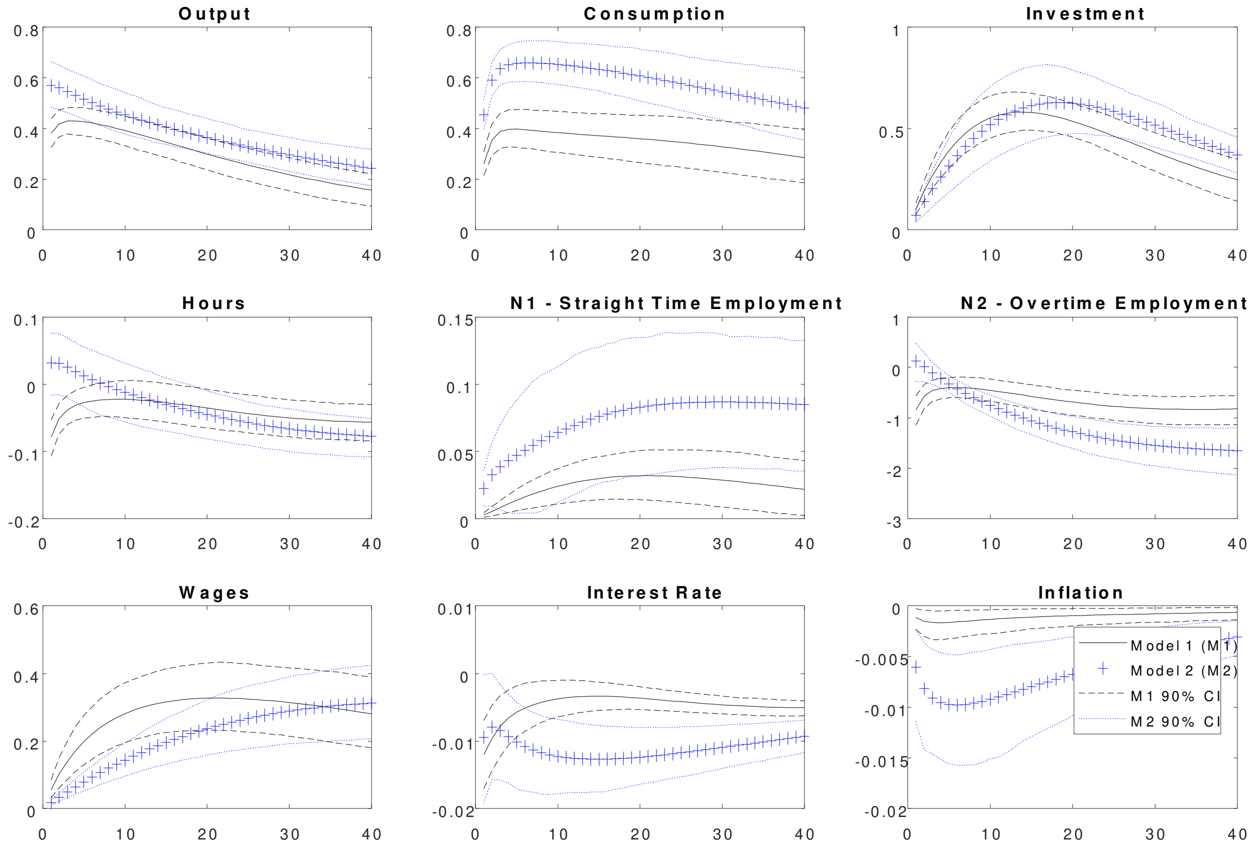

Figure 2: IRFs to a fiscal policy shock (Model 1 and Model 2)

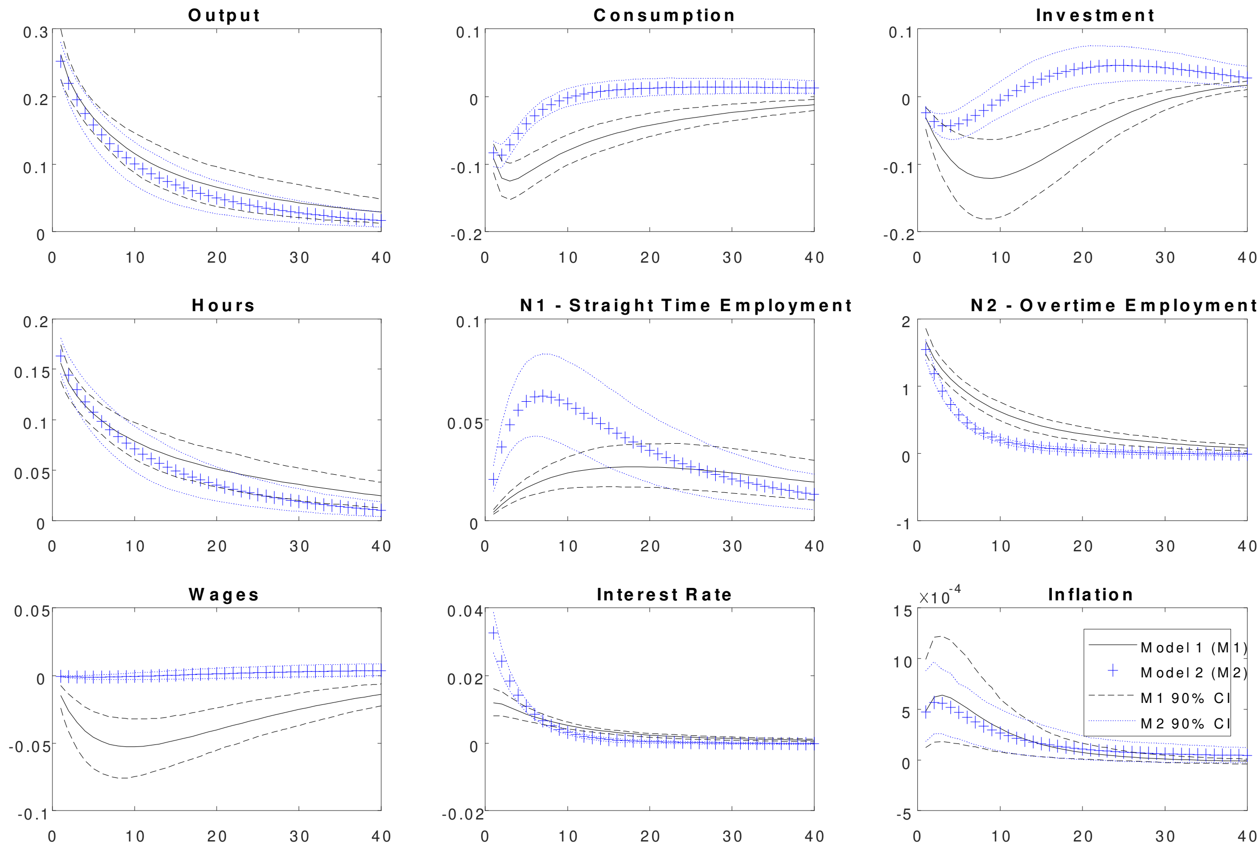

Figure 3: IRFs to a 1% temporary interest rate shock (Model 1, Model 2 and VAR ACEL)