Bayesian Estimation of a New Keynesian Model with Overtime Labor

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Abstract

I make use of a Bayesian likelihood approach to estimate a DSGE of the US economy using macro-economic time series. The estimated model is an extended version of the New Keynesian model with overtime labor developed in Madeira (2007). The goal is to verify whether the model can explain the main features of the US business cycle and how useful are the introduced labor frictions in describing the data series considered.

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Keywords: New Keynesian Phillips Curve, business cycle models, labor frictions, inflation dynamics, Bayesian estimation methods.

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1 Introduction

Models that combine price stickiness with monopoly power at the firm level (New Keynesian models) have become standard specifications and contributed greatly to a better understanding of short-run inflation dynamics.

In this paper I depart from the common assumption of rental spot labor markets in this class of models. I assume that firms must commit to the number of workers they will employ before observing shocks to the economy and face convex adjustment costs in changing their full time workers, but are free to adjust the number of employees working overtime in response to economic changes.

By estimating the model with Bayesian methods, I find that both predetermined employment and labor adjustment costs are important in order for the model to match aggregate US data. I also show that the model does not need a high degree of price stickiness at the firm level. I also find that the inflation objective, discount rate and labor supply shocks explain most of the business cycle fluctuations.

The model presented here builds on Madeira's (2007) paper, but shocks to the central banks inflation target, to the discount rate, labor supply, hiring expenses and price mark-up are introduced.

The work in this paper is also related to the literature on DSGE model estimation with Bayesian methods, having as main references recent papers by Smets and Wouters (2003 and 2007).

2 The Model Economy: An Overtime Model with Labor Frictions

2.1 Households

Consider an economy with a continuum of identical infinitely lived agents on the interval [0,1] who have preferences over consumption of a single nondurable good C_t and leisure L_t.

Their utility is:

$$\sum_{t=0}^{\infty} \beta^t \varepsilon_t^B \left(\tfrac{1}{1-\sigma} C_t^{1-\sigma} + \varepsilon_t^L \tfrac{v}{1-\chi} L_t^{1-\chi}\right), \qquad (1)$$

where $0<\beta<1$ is their subjective discount factor, v measures the utility from leisure and is strictly greater than zero, σ is the intertemporal elasticity of substitution and χ is the labor supply elasticity.

Equation (1) also contains two preference shocks: ε_t^B represents a shock to the discount rate that affects the intertemporal substitution of households and ε_t^L represents a shock to the labor supply. Both shocks are assumed to follow a first-order autoregressive process with an IID- Normal error term: $\varepsilon_t^B = \rho_b \varepsilon_{t-1}^B + \eta_t^B$ and $\varepsilon_t^L = \rho_b \varepsilon_{t-1}^L + \eta_t^L$.

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

-T if the agent is unemployed;

-T-t1 if the agent is employed but works the straight shift only;

-T-t1-t2 if the agent works both the straight and overtime shift.

I follow Hansen (1985) and Rogerson (1988) and employ lotteries to convexify the commodity space. The end result is the utility specification below (see appendix for details), similar to the one used by Hansen and Sargent (1988), Hall (1996) and Madeira (2007):

$$\sum_{t=0}^{\infty} \beta^t \varepsilon_t^B \left[\tfrac{1}{1-\sigma} C_t^{1-\sigma} - a_1 \varepsilon_t^L (N_{1,t} - N_{2,t}) - a_2 \varepsilon_t^L N_{2,t} - a_0 \varepsilon_t^L (1 - N_{1,t})\right], \qquad (2)$$

where $a_0 = -v\frac{1}{1-\chi}, a_1 = -v\frac{1}{1-\chi}(1-h_1)^{1-\chi}, a_2 = -v\frac{1}{1-\chi}(1-h_1-h_2)^{1-\chi}$, $h_1 =$ t1/T, $h_2 =$ t2/T (in order to normalize to unity the household's time endowment), $N_{1,t}$ is the share of agents who work the straight time shift (full time employment) and $N_{2,t}$ is the share of workers who work both shifts (overtime employment). This representative agent chooses a set of stochastic processes $\{C_t, N_{1,t}, N_{2,t}\}_{t=0}^{\infty}$ to maximize (2) subject to the following sequences of budget constraints:

$$C_t = (D_t + W_{1,t} h_1 N_{1,t} + W_{2,t} h_2 N_{2,t} + T_t + TR_t - E_t \{Q_{t,t+1} D_{t+1}\})/P_t, \qquad (3)$$

where P_t is the price of the final good, $W_{1,t}$ is the nominal hourly wage of the straight shift, $W_{2,t}$ is the nominal hourly wage of the overtime shift, D_t is the nominal payoff of the portfolio held at the end of period t, $Q_{t,t+1}$ is the stochastic discount factor, TR_t are government transfers and T_t denotes firms profits. The price of a one period bond is given by $R_t^{-1} = E_t Q_{t,t+1}$ where R_t denotes the gross nominal interest rate.

The resulting first order conditions are:

$$Q_{t,t+1} = \beta(C_{t+1}/C_t)^{-\sigma}(P_t/P_{t+1})(\varepsilon_t^B/\varepsilon_{t+1}^B), \qquad (4)$$

$$\varepsilon_t^B C_t{}^{-\sigma} w_{2,t} h_2 + \varepsilon_t^L [a_1 - a_2] = 0, \qquad (5)$$

$$\varepsilon_t^B C_t{}^{-\sigma} w_{1,t} h_1 + \varepsilon_t^L [a_0 - a_1] = 0, \qquad (6)$$

with

$$w_{2,t} = W_{2,t}/P_t, \qquad (7)$$

$$w_{1,t} = W_{1,t}/P_t, \qquad (8)$$

2.2 Firms

2.2.1 Final Good Firms

The final consumption good, Y_t, is produced by a perfectly competitive representative firm. The firm produces the final good by combining a continuum of intermediate goods ($Y_i, i \in [0,1]$) using a Dixit-Stiglitz technology:

$$Y_t = [\int_0^1 Y_{i,t}^{1/(1+\lambda_{P,t})} di]^{1+\lambda_{P,t}}, \qquad (9)$$

where $\lambda_{P,t}$ is a stochastic parameter that determines the time-varying mark-up in the goods market. I assume that $\lambda_{P,t} = \lambda_P + \eta_t^P$, where η_t^P is IID- Normal.

Profit maximization implies the following demand for the ith good:

$$Y_{i,t} = (P_t/P_{i,t})^{(1+\lambda_{P,t})/\lambda_{P,t}} Y_t, \qquad (10)$$

where P_t is an index cost of buying a unit of Y:

$$P_t = [\int_0^1 P_{i,t}^{--1/\lambda_{P,t}} di]^{-\lambda_{P,t}}. \qquad (11)$$

2.2.2 Intermediate Good Firms

Each intermediate good is produced by a monopolist firm according to the following production function:

$$Y_{i,t} = A_t N_{i,t} \;, \qquad (7)$$

$$N_{i,t} = (h_1 N_{1,t}^{1-\alpha}(i) + h_2 N_{2,t}^{1-\alpha}(i)). \qquad (8)$$

A_t is a productivity shock which is assumed to follow an exogenous AR(1) process: $\ln A_t = \rho_a \ln A_{t-1} + \eta_t^A$, where η_t^A represents a shock distributed independently N(0, 1). The above production function is similar to the one used by Hall (1996). Like Hall, I assume $N_{1,t}(i)$ must be chosen before the shocks to the economy are known[1]. Intermediate good producers are subject to Calvo price staggering. They also face labor adjustment costs[2] to total employment[3], according to:

$$H_{i,t} = H(\varepsilon_t^H \tfrac{N_{1,t+1}(i)}{N_{1,t}(i)}) N_{1,t}(i), \qquad (9)$$

where $H_{i,t}$ represent purchases by the firm of the final good. The function H(.) is an increasing and convex function, of the usual kind assumed in neoclassical investment theory, which satisfies near a zero growth rate of employment, H(1)=δ_{N1}, H'(1)=1 and H"(1)=$\epsilon_{\psi N1}$, where δ_{N1} is an exogenous separation rate and the parameter $\epsilon_{\psi N1}$ measures the employment adjustment costs in a log-linear approximation to the equilibrium dynamics. This implies that in the steady state to which the economy converges in the absence of shocks, the rate of hiring required to maintain the economy's employment is δ_{N1} times the steady state employment N1 (so that δ_{N1} can be interpreted as the exogenous quit rate in employment). It also implies that near the steady state, a marginal unit in hiring expenses increases employment by an equal amount (as there are locally

[1] Studies using aggregate quarterly data, summarized in Hamermesh (1993), show the average lag in adjusting employment demand to be three to 6 months.

[2] Empirical studies at the micro level indicate that labor adjustment costs are quite significant (see Hamermesh and Pfann (1996) for a survey), with some suggesting they amount to as much as one year payroll for the average worker.

[3] Sargent (1978) and Shapiro (1986) using aggregate data estimated adjustment costs for overtime to be much smaller than for employment levels. For this reason I assume there are no adjustment costs to overtime employment.

no adjustment costs). These assumptions are similar to those made by Woodford (2005) and Sveen and Weinke (2004) in a context of investment adjustment costs.

I also introduce a shock to the labor adjustment cost function, which is assumed to follow a first-order autoregressive process with an IID- Normal error term: $\varepsilon_t^H = \rho_b \varepsilon_{t-1}^H + \eta_t^H$.

The present discounted value of profits is:

$$E_t \sum_{j=0}^{\infty} Q_{t,t+j}[P_{i,t+j}Y_{i,t+j} - P_{t+j}w_{1,t+j}h_1 N_{1,t+j}(i) - P_{t+j}w_{2,t+j}h_2 N_{2,t+j}(i) - P_{t+j}H_{i,t+j}], \qquad (10)$$

where $w_{1,t}$ is the real hourly wage of the straight shift and $w_{2,t}$ is the real hourly wage of the overtime shift. The ith intermediate good firm chooses $P_{i,t+j}, Y_{i,t+j}, N_{1,t+j+1}(i), N_{2,t+j}(i)$ to maximize profits subject to (5), (7), (9), as well as its price setting constraints. The firm takes P_{t+j}, $Y_{t+j}, W_{1,t+j}, W_{2,t+j}$ as given.

The resulting first order conditions are:

$$E_t \sum_{j=0}^{\infty} (\theta\beta)^j \Lambda_{t,j} \tfrac{P_{t+j}}{P_{t+j+1}} Y_{i,t+j}[P_{i,t} - (1+\lambda_{P,t})MC_{i,t+j})] = 0, \qquad (11)$$

$$\tfrac{w_{2t}}{(1-\alpha)A_t N_{2,t}^{-\alpha}(i)} = MC_{it}, \qquad (12)$$

$$H'(\varepsilon_t^H \tfrac{N_{1,t+1}(i)}{N_{1,t}(i)}) = E_t \beta \Lambda_{t,1}[\rho_{i,t+1} + \tfrac{N_{1,t+2}(i)}{N_{1,t+1}(i)} \varepsilon_{t+1}^H H'(\varepsilon_{t+1}^H \tfrac{N_{1,t+2}(i)}{N_{1,t+1}(i)}) - H(\varepsilon_{t+1}^H \tfrac{N_{1,t+2}(i)}{N_{1,t+1}(i)})], \qquad (13)$$

with:

$$\rho_{i,t+1} = -w_{1,t+1}h_1 + w_{2,t+1}h_2 \tfrac{MPN_{1,t+1}(i)}{MPN_{2,t+1}(i)}, \qquad (14)$$

$$\tfrac{MPN_{1,t+1}(i)}{MPN_{2,t+1}(i)} = N_{2,t+1}^{\alpha}(i) \tfrac{h_1}{h_2} N_{1,t+1}^{-\alpha}(i) = [\tfrac{1}{h_2} Y_{i,t+1} A_{t+1}^{-1} - \tfrac{h_1}{h_2} N_{1,t+1}^{1-\alpha}(i)]^{\alpha/(1-\alpha)} \tfrac{h_1}{h_2} N_{1,t+1}^{-\alpha}(i), \qquad (15)$$

and $\Lambda_{t,j} = (\lambda_{t+j}/\lambda_t) = (\varepsilon_{t+j}^B C_{t+j}^{-\sigma}/(\varepsilon_t^B C_t{}^{-\sigma}), 1 + \lambda_{P,t}$ is the markup of price over marginal cost when prices are perfectly flexible, θ is the probability the firm will not be able to optimally reset its price this period.

The first order condition for the firm's price setting behavior (equation 11) is similar to the standard New Keynesian model (price is a function of all future expected marginal costs). However, since a firm's choice of full time employment is among the determinants of its marginal product of labor, I cannot solve the price setting problem without considering the firm's optimal employment behavior. The reason for this is that N1 is not purchased on a spot market. A firm's marginal cost therefore depends on its present full time employment numbers and these depend on the firm's decisions in previous periods, including its price-setting decisions. The firm's choices here are more complex than in standard sticky price models (which typically assume rental markets for production factors) but the problem is very similar to the case of firm-specific capital solved by Woodford (2005).

Equation (12) is also important. It implies that when straight time employment is predetermined, the relevant measure of a firm's marginal cost is its overtime labor costs and not its total labor input.

Equation (13) takes a similar form to the F.O.C. for the firm's investment decision found in Sveen and Weinke (2004) or Woodford (2005). It is noteworthy that a firm's marginal return to N1 is measured by the marginal savings in its overtime costs as opposed to its marginal productivity. This arises from the firms being demand constrained, which implies that the firm's benefit from having an additional worker derives from the fact that this allows to produce the quantity demanded with less overtime work.

2.3 Aggregate Resource Constraint

From now on, I will use lower case letters to denote variables in log deviation from the steady state.

The economy's resource constraint is:

$$Y_t = C_t + G_t + H_t, \qquad (16)$$

where

$$H_t = [\int_0^1 H_{it} di], \qquad (17)$$

and G_t denotes government expenses. I assume that government adjusts lump sum taxes to ensure that its intertemporal budget constraint holds. Total output is allocated to private consumption, government expenses and hiring expenses. It is assumed that government spending follows an exogenous AR(1) process: $g_t = \rho_g g_{t-1} + \eta_t^B$, where η_t^B represents a shock distributed independently N(0, 1).

2.4 Inflation Dynamics

The economy's price inflation equation takes the form (see appendix for details):

$$\pi_t = \beta E_t \pi_{t+1} + \gamma(mc_t + \eta_t^P), \qquad (18)$$

where $\pi_t = p_t - p_{t-1}$ and the parameter γ is a function of the model's structural parameters ($\gamma = \frac{(1-\theta)(1-\theta\beta)}{\theta}\phi_{N1}^{-1}$, in the homogeneous factors model $\phi_{N1} = 1$) which is computed numerically using the method developed in Woodford (2005). Woodford (2005) shows that a non-explosive solution to the firm's decision problem exists in the case of large enough adjustment costs. The introduction of labor frictions does not imply any important change in the dynamic relationship between inflation and average real marginal cost in comparison to the baseline NKPC model (such as Yun (1996)), only the numerical magnitude of γ is affected by the size of the adjustment costs to labor. In particular, the predicted slope of the Phillips curve trade-off can be affected to an extent that is quantitatively significant.

2.5 Monetary Policy Rule

When prices are sticky the equilibrium path of real variables cannot be determined independently of monetary policy. In other words: monetary policy is non-neutral. The model is closed by assuming the central bank follows a simple interest rule (often referred to as a Taylor rule) of the form:

$$i_t = \rho_i i_{t-1} + \gamma_\pi(\pi_t - \bar{\pi}_t) + \gamma_y y_t + \eta_t^R. \qquad (19)$$

This rule has desirable stabilizing properties[4] and also some empirical appeal as a description of what central banks do in practice. I assume there are two monetary policy shocks: one is a persistent

[4] The central bank chooses a target for the short term interest rate, as a function of economic conditions. To attain that rate, the central bank adjusts the money supply to meet the quantity on money demanded at the target interest rate. This is preferable than doing the reverse (set the nominal money stock and let the interest rate adjust), due to the potential instability of money demand suggested by the evidence. Under monetary targeting, this instability would translate into interest rate volatility that could harm the real economy.

shock to the inflation objective ($\bar{\pi}_t$) which is assumed to follow a first-order autoregressive process with an IID- Normal error term: $\bar{\pi}_t = \rho_\pi \bar{\pi}_{t-1} + \eta_t^\pi$ and the other is a temporary IID-Normal interest rate shock (η_t^R).

3 Estimation Results

3.1 Estimation Methodology

The model presented in the previous section is estimated with Bayesian estimation techniques using demeaned quarterly US time series data: HP detrended log of consumption, HP detrended log of government expenditures, HP detrended log of real GDP, HP detrended log N1, HP detrended log N2, HP detrended log real wages, the federal funds rate and inflation. More details about the dataset used can be found in the appendix.

First, I estimate the mode and standard deviation of the posterior distribution by maximizing the log posterior function, which combines the prior information on the parameters with the likelihood of the data. The log data density is then obtained by Laplace approximation. In a second step, the Metropolis-Hastings algorithm is used to get a complete picture of the posterior distribution and to evaluate the marginal likelihood of the model (Harmonic mean estimation).

I now proceed to discuss the choice of prior distribution. A number of parameters were kept fixed from the start of the exercise. Most of these parameters can be directly related to the steady-state values of the state variables and could therefore be estimated from the means of the observable variables. However, given that the data set is demeaned, it is not possible to pin them down in the estimation procedure. The discount rate is set at $\beta = 0.99$ and I assume a value of one for σ, the intertemporal elasticity of substitution. The period length is one quarter The representative agent's leisure utility parameter v and the labor supply elasticity χ are calibrated so that N1=0.42 and N2=0.16 (their time series means). The agents time endowment T is set at 1369, implying agent's have 15 hours per day available for work and leisure activities. I assume the straight time shift to be 40 hours a week, implying a quarterly value of 516 for t1. I choose the overtime shift t2 to be equal to 155, the mean of overtime hours (see Madeira (2007) for more details). The capital share α is 0.33 and the GDP share of government expenses equals 0.2, both are standard values in the business cycle literature. The quit rate in employment (δ_{N1}) is chosen to be 0.1 (consistent with the empirical evidence for the U.S., see Shimer (2005)).

The first three columns of Table 1 give an overview of the assumptions made regarding the prior distribution of the other 19 estimated parameters. Following Smets and Wouters (2003), I assume all the standard deviations of the shocks to follow an inverted Gamma distribution. The precise mean for the prior was based on previous estimation outcomes. The distribution of the autoregressive parameters

was assumed to follow a beta distribution and again, the precise mean for the prior was based on previous estimation outcomes.The prior mean on $\epsilon_{\psi N1}$, the curvature on labor adjustment costs, was set at 1.27. Cooper and Willis (2002) results suggest this value to be around 2, while Ejarque and Portugal (2006) estimate it around 0.5. Due to the large disparities in empirical estimates, I chose a prior in the center of these values and with a standard deviation of 2. The New Keynesian Phillips curve coefficient for marginal cost γ is set at 0.03[5], which is consistent with empirical estimates (see Gali and Gertler (1999)). For the Taylor rule I choose the mean prior inflation and output weights (γ_π, γ_y) to be 1.44 and 0.18 respectively, which are consistent with observed variations in the Federal Funds rate over the Greenspan era (see Taylor (1999)). The prior mean on the lagged interest rate is set at 0.94 which is consistent with the estimates of Clarida, Gali and Gertler (2000).

3.2 Parameter Estimates

In addition to the prior distribution, Table 1 reports two sets of results regarding the parameter estimates. The first set contains the estimated posterior mode of the parameters, which is obtained by directly maximising the log of the posterior distribution with respect to the parameters, and am approximate standard error based on the corresponding Hessian. The second set reports the 5 and 95 percentile of the posterior distribution of the parameters obtained through 500 000 draws of the Metropolis- Hastings sampling algorithm. Overall,the estimated mode is fairly close (the few exceptions are the standard deviations of the produtivity, government spending and interest rate shocks) to the prior mean and most parameters are estimated to be significant. Of particular interest is the NKPC coefficient on marginal cost. This is estimated to be 0.042 (implying a value

[5] In the presence of frictions on factor inputs the Calvo price stickiness parameter cannot be directly estimated from the data (Woodford (2005)).

of 0.345 for the Calvo price stickiness parameter, if one assumes a 15% price mark-up, which is consistent with the micro evidence on price frequency adjustment) which is both significant and positive. The estimates suggest that the inflation objective, discount rate, labor supply and price mark-up shocks are quantitatively more important than the other shocks. However, these are also the parameters with higher standard deviations (particularly the inflation objective and discount rate shocks).

These estimates appear to be fairly robust as can be seen by comparing the results of Table 1 with those of Table 2, obtained under much less strict priors (the standard deviation of the prior distribution in Table 2 is twice that of Table 1).

3.3 Which Frictions are Empirically Important?

The marginal likelihood of the model gives an indication of the overall likelihood of the model given the data and reflects its prediction performance. Comparing the model considered here with one with no labor frictions (employment is not predetermined and there are no labor adjustment costs), I find that labor frictions are empirically important, since the model with no frictions has lower marginal likelihood (under both the Laplace approximation and Harmonic mean estimation). The resulting parameter estimates can be seen on Table 3. Table 4 displays the results of the model with labor frictions detailed in section 2, but with sharply reduce labor adjustment costs. This also results in a significant decrease in the model's marginal likelihood. I also explore if a high degree of price stickiness is indeed needed in this model (as in the standard model) in order to achieve a better fit to the aggregate data. Table 5 reports the estimation results in the case where the NKPC coefficient on marginal cost is reduced to 0.006. This implies a value of 0.642 for the Calvo price stickiness parameter, if one assumes a 15% price mark-up. The significant reduction in the model's likelihood confirms that in a model that takes into account frictions in the labor market there is no need to impose a large degree of price stickiness in order to explain the main features of the US business cycle.

3.4 Comparison of Model Based Moments with the Data

Table 6 and 7 show the contemporaneous correlation and the relative standard deviation of the endogenous variables with respect to output (for the model with labor frictions, a model with no labor frictions and the US data). The model with labor frictions seems to match the data somewhat better with respect to relative standard deviations (specially in the case of consumption and wages) but worse in the case of contemporaneous correlations (particularly in the case of N2).

4 What structural shocks explain business cycle fluctuations?

Table 6 and 7 also show the contributions of each shock to account for movements in the endogenous variables of both the model with labor frictions and a model with no labor frictions. In both cases, the inflation objective, discount rate and labor supply shocks explain most of the business cycle fluctuations. In the model with no frictions, the inflation objective shocks have relatively less importance, whereas the discount rate and labor supply shocks are relatively more important. These results are somewhat consistent with Smets and Wouters (2003) findings which suggested that labor supply, productivity, interest rate and discount rate shocks were the most important in explaing business cycle fluctuations for the euro area.

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5 Appendix

5.1 Data

The employment and hours data series used in this paper are aggregate data in U.S. nonagricultural industries from the BLS's Current Population Survey. N1 denotes the number of full time workers (persons who worked 35 hours and over a week), finally N2 denotes overtime employment (number of persons who worked 41 hours and over a week). Data for N1 and N2, data covers the period 1955Q1-2006Q4[6]. Data regarding employment numbers was converted to quarterly by averaging monthly observations and was subsequentially seasonally adjusted. Per capita variables were constructed by dividing by civilian noninstitutional population NSA from the BLS.

The inflation measure is the log difference of the GDP deflator, the output gap is obtained by HP detrending real GDP, real wages is the log of compensation per hour in the nonfarm business sector minus the log of the GDP deflator, consumption is personal consumption expenditures and goverment spending is goverment current expenditures. I detail below the series just mentioned and others used in the paper:

CNP16OV Civilian Noninstitutional Population; source:BLS; 1948Q1-2007:Q1

COMPNFB Nonfarm Business Sector: Compensation Per Hour; source:BLS; 1947Q1-2007:Q1.

GDP Gross Domestic Product; source:BEA; 1947Q1-2007:Q1.

Real GDP Gross Domestic Product; source:BEA; 1947Q1-2007:Q1

GDPDEF Gross Domestic Product: Implicit Price Deflator; source: BEA; 1947Q1-2007:Q1.

GEXPND Government Current Expenditures; source: BEA; 1947Q1-2007:Q1.

PCEC Personal Consumption Expenditures; source: BEA; 1947Q1-2007:Q1.

FEDFUNDS Effective Federal Funds Rate; source: BEA; 1954M7-2007:M6.

CNP16OV, COMPFNB, GDP, Real GDP, GDPDEF, GEXPND, PCEC and the FEDFUNDS were downloaded from the St. Louis Fed website, the remaining series were downloaded from the Economagic website. CNP16OV, COMPFNB and FEDFEUNDS were converted to quarterly by averaging the monthly observations.

[6] I'm grateful to George Hall for sharing his data on full time and overtime employment from 1955 to 1992.

5.2 Representative Agent's Utility Function

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 utilitity, after normalizing the agent's time endowment to unity, is then:

$\pi_{1,t}[\frac{1}{1-\sigma}{C_t}^{1-\sigma} + \varepsilon_t^L \frac{v}{1-\chi}(1-h_1)^{1-\chi}] + \pi_{2,t}[\frac{1}{1-\sigma}{C_t}^{1-\sigma} + \varepsilon_t^L \frac{v}{1-\chi}(1-h_1-h_2)^{1-\chi}] + (1-\pi_{1,t} - \pi_{2,t})[\frac{1}{1-\sigma}{C_t}^{1-\sigma} + \varepsilon_t^L \frac{v}{1-\chi}(1)^{1-\chi}]. \qquad (A1)$

Define $N_{1,t}$ to be the share of agents who work the straight time shift (full time employment) and $N_{2,t}$ the share of agents who work both shifts(overtime employment). So $N_{1,t} = \pi_{1,t} + \pi_{2,t}$ and $N_{2,t} = \pi_{2,t}$. Since capital markets are complete (consumption is the same for all agents), one can write the representative agent's utility function as:

$$\max \sum_{t=0}^{\infty} \beta^t \varepsilon_t^B [\tfrac{1}{1-\sigma}{C_t}^{1-\sigma} - a_1 \varepsilon_t^L (N_{1,t} - N_{2,t}) - a_2 \varepsilon_t^L N_{2,t} - a_0 \varepsilon_t^L (1 - N_{1,t})], \qquad (A2)$$

where $a_0 = -v\frac{1}{1-\chi}, a_1 = -v\frac{1}{1-\chi}(1-h_1)^{1-\chi}, a_2 = -v\frac{1}{1-\chi}(1-h_1-h_2)^{1-\chi}$.

5.3 Steady State

5.3.1 Overtime model with Labor Frictions

In steady state, (8), (9) and (14) reduce to:

$$N = (h_1 N_1^{1-\alpha} + h_2 N_2^{1-\alpha}),$$

$$H = \delta_{N1} N_1,$$

$$\rho = 1/\beta - (1 - \delta_{N1}).$$

From the production function it is simple to obtain Y:

$$Y = AN,$$

and then obtain the steady state consumption from the resource constraint:

$$C = (1 - sg)Y - H = w_1 h_1 N_1 + w_2 h_2 N_2,$$

where sg=G/Y.

Steady state values for w_1, w_2, v and χ are obtained by solving the system of equations:

$$w_2 = ((a_2 - a_1)C^{\sigma})/h_2,$$

$$w_1 = ((a_1 - a_0)C^{\sigma})/h_1,$$

$$MC = 1/\mu = \frac{w_2}{(1-\alpha)AN_2^{-\alpha}},$$

5.4 Log-Linear Expansions

From now on, I will use lower case letters or hats to denote variables in log deviation from the steady state. I start by log-linearizing the representative agent first order conditions:

$$c_t = E_t c_{t+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1} + \log \beta - \hat{\varepsilon}_t^B + E_t \hat{\varepsilon}_{t+1}^B), \qquad (A3)$$

$$\hat{w}_{2,t} = \hat{\varepsilon}_t^B + \sigma c_t - \hat{\varepsilon}_t^L, \qquad (A4)$$

$$\hat{w}_{1,t} = \hat{\varepsilon}_t^B + \sigma c_t - \hat{\varepsilon}_t^L. \qquad (A5)$$

The log-linearized aggregate production function, labor adjustment cost function and aggregate resource constraint are:

$$Y y_t = a_t + (1 - \alpha) h_1 N_1^{1-\alpha} n_{1,t} + (1 - \alpha) h_2 N_2^{1-\alpha} n_{2,t}\ , \qquad (A6)$$

$$\delta_{N1} h_t = n_{1,t+1} - (1 - \delta_{N1}) n_{1,t}\ , \qquad (A7)$$

$$Y y_t = C c_t + sgY g_t + H h_t. \qquad (A8)$$

The law of motion of aggregate total employment is:

$n_{1,t+1} = \frac{1}{1+\beta} n_{1,t} + E_t \frac{\beta}{1+\beta} n_{1,t+2} + \frac{1-\beta(1-\delta_{N1})}{(1+\beta)\epsilon_{\psi N1}} E_t \hat{\rho}_{t+1} - \frac{1}{\epsilon_{\psi N1}} E_t(i_t - E_t \pi_{t+1} + \log \beta) - \frac{1}{1+\beta} \hat{\varepsilon}_t^H + \frac{\beta}{1+\beta} E_t \hat{\varepsilon}_{t+1}^H, \quad (A9)$

with:

$$\hat{\rho}_{t+1} = -\hat{w}_{1,t+1}\rho_{W1} + \hat{w}_{2,t+1}\rho_{W2} + y_{t+1}\rho_Y - a_{t+1}\rho_A - n_{1,t+1}\rho_{N1}. \qquad (A10)$$

The economy's price inflation equation takes the form:

$$\pi_t = \beta E_t \pi_{t+1} + \gamma(mc_t + \eta_t^P), \qquad (A11)$$

5.5 Tables

Table 1: Parameter estimates

	Prior distribution			Estimated maximum posterior			
parameters	type	Mean	St. Dev.	Mode	St. Dev.	5%	95%
σ produtivity shock	inv. gamma	0.05	1	0.0059	0.0881	0.0061	0.0065
σ inflation obj. shock	inv. gamma	0.04	1	0.0451	1.4718	0.0363	0.0433
σ discount rate shock	inv. gamma	0.04	1	0.0405	0.4921	0.0426	0.0453
σ government spending shock	inv. gamma	0.04	1	0.0077	0.008	0.0078	0.0079
σ labor supply shock	inv. gamma	0.13	1	0.1203	0.0762	0.1189	0.1202
σ hiring shock	inv. gamma	0.03	1	0.0236	0.033	0.0238	0.0241
σ interest rate shock	inv. gamma	0.01	1	0.0044	0.0009	0.0044	0.0044
σ price mark-up shock	inv. gamma	0.14	1	0.1433	0.0908	0.1442	0.1458
ρ produtivity shock	beta	0.8	0.1	0.7974	0.002	0.7972	0.7974
ρ inflation obj. shock	beta	0.8	0.1	0.8048	0.0002	0.8048	0.8048
ρ government spending shock	beta	0.64	0.1	0.6402	0.0019	0.6403	0.6406
ρ labor supply shock	beta	0.95	0.1	0.9521	0.0025	0.952	0.9522
ρ discount rate shock	beta	0.87	0.1	0.8677	0.0318	0.8675	0.8683
ρ hiring shock	beta	0.4	0.1	0.3946	0.0025	0.3945	0.3946
hiring adj. cost	Normal	1.27	2	1.2714	0.0005	1.2715	1.2716
ρ lagged interest rate	beta	0.94	0.1	0.9327	0.0005	0.9326	0.9327
γ inflation target	Normal	1.44	0.25	1.4403	0.0007	1.4401	1.4403
γ output gap	Normal	0.18	0.1	0.1798	0.0004	0.1796	0.1797
γ marginal cost	Normal	0.03	0.1	0.0418	0.0001	0.0418	0.0418

Log data density [Laplace approximation] is 3744.3419
Log data density [Harmonic mean estimation] is 3720.8968

Table 2: Parameter estimates with increased standard deviation of prior distribution

	Prior distribution			Estimated maximum posterior			
parameters	type	Mean	St. Dev.	Mode	St. Dev.	5%	95%
σ produtivity shock	inv. gamma	0.05	2	0.0059	0.1462	0.0062	0.0066
σ inflation obj. shock	inv. gamma	0.04	2	0.0288	1.0485	0.0252	0.0287
σ discount rate shock	inv. gamma	0.04	2	0.0404	0.0672	0.0382	0.0398
σ government spending shock	inv. gamma	0.04	2	0.0116	0.1702	0.0107	0.0117
σ labor supply shock	inv. gamma	0.13	2	0.0915	1.1158	0.0842	0.0886
σ hiring shock	inv. gamma	0.03	2	0.0296	1.0192	0.0245	0.0275
σ interest rate shock	inv. gamma	0.01	2	0.0047	0.0288	0.0042	0.0044
σ price mark-up shock	inv. gamma	0.14	2	0.1513	2.0964	0.1485	0.1558
ρ produtivity shock	beta	0.8	0.2	0.7913	0.0016	0.7813	0.7813
ρ inflation obj. shock	beta	0.8	0.2	0.877	0.0001	0.877	0.877
ρ government spending shock	beta	0.64	0.2	0.6442	0.0024	0.6443	0.6445
ρ labor supply shock	beta	0.95	0.2	0.9528	0.0026	0.9527	0.9529
ρ discount rate shock	beta	0.87	0.2	0.8697	1.0385	0.8629	0.8698
ρ hiring shock	beta	0.4	0.2	0.3902	0.0013	0.3901	0.3902
hiring adj. cost	Normal	1.27	4	1.2652	0.0009	1.2651	1.2653
ρ lagged interest rate	beta	0.94	0.2	0.927	0.0001	0.927	0.927
γ inflation target	Normal	1.44	0.5	1.4412	0	1.4412	1.4412
γ output gap	Normal	0.18	0.2	0.1817	0	0.1816	0.1817
γ marginal cost	Normal	0.03	0.2	0.0432	0	0.0432	0.0432

Log data density [Laplace approximation] is 3892.0619
Log data density [Harmonic mean estimation] is 3864.2871

Table 3: Parameter estimates NK model with no labor frictions

	Prior distribution			Estimated maximum posterior			
parameters	type	Mean	St. Dev.	Mode	St. Dev.	5%	95%
σ produtivity shock	inv. gamma	0.05	1	0.0059	0.0187	0.0059	0.006
σ inflation obj. shock	inv. gamma	0.04	1	0.0053	0.0089	0.0048	0.006
σ discount rate shock	inv. gamma	0.04	1	0.0365	0.133	0.0298	0.0358
σ government spending shock	inv. gamma	0.04	1	0.0136	0.0619	0.0099	0.0116
σ labor supply shock	inv. gamma	0.13	1	0.1089	0.0425	0.0836	0.09
σ interest rate shock	inv. gamma	0.01	1	0.0018	0.0004	0.0019	0.0019
σ price mark-up shock	inv. gamma	0.14	1	0.1411	0.0788	0.1547	0.1611
ρ produtivity shock	beta	0.8	0.1	0.7998	0.0813	0.7972	0.7974
ρ inflation obj. shock	beta	0.8	0.1	0.7972	0.0029	0.8048	0.8048
ρ government spending shock	beta	0.64	0.1	0.6401	0.0101	0.6403	0.6406
ρ labor supply shock	beta	0.95	0.1	0.9649	0.0077	0.952	0.9522
ρ discount rate shock	beta	0.87	0.1	0.8694	0.1995	0.8675	0.8683
ρ lagged interest rate	beta	0.94	0.1	0.9274	0.0002	0.9326	0.9327
γ inflation target	Normal	1.44	0.25	1.4405	0.0014	1.4401	1.4403
γ output gap	Normal	0.18	0.1	0.1814	0.0011	0.1796	0.1797
γ marginal cost	Normal	0.03	0.1	0.0301	0	0.0418	0.0418

Log data density [Laplace approximation] is 3349.1562
Log data density [Harmonic mean estimation] is 3400.1660

Table 4: Parameter estimates reduced labor adjustment costs

	Prior distribution			Estimated maximum posterior			
parameters	type	Mean	St. Dev.	Mode	St. Dev.	5%	95%
σ produtivity shock	inv. gamma	0.05	1	0.0142	0.0365	0.0059	0.0059
σ inflation obj. shock	inv. gamma	0.04	1	0.0146	0.8614	0.0047	0.0245
σ discount rate shock	inv. gamma	0.04	1	0.1009	0.3247	0.0352	0.0397
σ government spending shock	inv. gamma	0.04	1	0.0203	0.4891	0.0111	0.0133
σ labor supply shock	inv. gamma	0.13	1	0.0154	0.0009	0.0155	0.0155
σ hiring shock	inv. gamma	0.03	1	0.0239	0.0124	0.0234	0.0238
σ interest rate shock	inv. gamma	0.01	1	0.0055	0.0343	0.0028	0.0031
σ price mark-up shock	inv. gamma	0.14	1	0.147	0.0838	0.1633	0.1655
ρ produtivity shock	beta	0.8	0.1	0.7254	0.6355	0.666	0.6707
ρ inflation obj. shock	beta	0.8	0.1	0.9319	0.0145	0.9236	0.9248
ρ government spending shock	beta	0.64	0.1	0.6091	0.0176	0.6039	0.6048
ρ labor supply shock	beta	0.95	0.1	0.9087	0.3745	0.8897	0.8926
ρ discount rate shock	beta	0.87	0.1	0.7796	9.7545	0.0697	0.0903
ρ hiring shock	beta	0.4	0.1	0.3666	0.6465	0.2746	0.2832
hiring adj. cost		0.254					
ρ lagged interest rate	beta	0.94	0.1	0.8253	0.0063	0.8264	0.827
γ inflation target	Normal	1.44	0.25	1.4686	0.023	1.4808	1.4852
γ output gap	Normal	0.18	0.1	0.0569	0.0005	0.0571	0.0571
γ marginal cost	Normal	0.03	0.1	-0.0304	0.0002	-0.0303	-0.0303

Log data density [Laplace approximation] is 2644.4576
Log data density [Harmonic mean estimation] is -Inf.

Table 5: Parameter estimates increased price stickiness

	Prior distribution			Estimated maximum posterior			
parameters	type	Mean	St. Dev.	Mode	St. Dev.	5%	95%
σ produtivity shock	inv. gamma	0.05	1	0.0059	0.0477	0.0067	0.0073
σ inflation obj. shock	inv. gamma	0.04	1	0.0297	0.3207	0.0208	0.0247
σ discount rate shock	inv. gamma	0.04	1	0.0832	0.1989	0.0689	0.0734
σ government spending shock	inv. gamma	0.04	1	0.0078	0.0069	0.0079	0.0081
σ labor supply shock	inv. gamma	0.13	1	0.1112	0.0561	0.1056	0.1085
σ hiring shock	inv. gamma	0.03	1	0.0228	0.0189	0.0249	0.0259
σ interest rate shock	inv. gamma	0.01	1	0.097	0.0098	0.0957	0.0961
σ price mark-up shock	inv. gamma	0.14	1	0.4941	0.0104	0.4946	0.4955
ρ produtivity shock	beta	0.8	0.1	0.7967	0.0045	0.7983	0.8006
ρ inflation obj. shock	beta	0.8	0.1	0.8072	0.001	0.8073	0.8081
ρ government spending shock	beta	0.64	0.1	0.6407	0.0018	0.6412	0.6419
ρ labor supply shock	beta	0.95	0.1	0.8224	0.0229	0.8169	0.8206
ρ discount rate shock	beta	0.87	0.1	0.8848	0.0214	0.8878	0.8914
ρ hiring shock	beta	0.4	0.1	0.3899	0.0032	0.3906	0.3914
hiring adj. cost	Normal	1.27	2	1.2619	0.0005	1.2646	1.273
ρ lagged interest rate	beta	0.94	0.1	0.9452	0.0005	0.9444	0.9454
γ inflation target	Normal	1.44	0.25	1.4399	0.0007	1.4417	1.4409
γ output gap	Normal	0.18	0.1	0.1824	0.0004	0.1834	0.1825
γ marginal cost	Normal	0.006					

Log data density [Laplace approximation] is 2897.2129
Log data density [Harmonic mean estimation] is 2926.2145

Table 6: variance decomposition

	c	i	n1	n2	inflation	w	y
produtivity shock	0.19	0.19	0.19	0.57	0.21	0.19	0.20
inflation obj. shock	22.34	21.86	22.22	22.33	21.68	21.75	22.44
discount rate shock	1.42	1.34	1.35	1.71	1.36	1.33	1.39
government spending shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
labor supply shock	75.17	75.72	75.36	74.18	75.87	75.87	75.06
hiring shock	0.22	0.22	0.22	0.41	0.23	0.21	0.24
interest rate shock	0.65	0.64	0.65	0.78	0.63	0.64	0.66
price mark-up shock	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Rel. St. Dev. (model)	0.98	0.40	1.64	3.44	0.40	0.98	1.00
Rel. St. Dev. (data)	0.61	0.51	1.23	2.23	0.40	0.55	1.00
Contemp. Corr. with y (model)	1.00	-0.99	1.00	-0.89	-0.97	0.98	1.00
Contemp. Corr. with y(data)	0.88	0.38	0.60	0.73	0.18	0.12	1.00

Table 7: variance decomposition (no labor frictions)

	c	i	n1	n2	inflation	w	y
produtivity shock	0.08	0.05	6.76	6.76	0.16	0.06	0.08
inflation obj. shock	1.64	0.01	1.53	1.53	1.09	1.27	1.64
discount rate shock	4.47	0.01	4.17	4.17	0.33	1.16	4.47
government spending shock	0.00	0.00	0.04	0.04	0.00	0.00	0.04
labor supply shock	92.95	99.58	86.70	86.70	97.63	96.85	92.91
interest rate shock	0.80	0.34	0.75	0.75	0.32	0.62	0.80
price mark-up shock	0.05	0.02	0.05	0.05	0.46	0.04	0.05
Rel. St. Dev. (model)	1.58	0.29	1.51	1.51	0.43	1.80	1.00
Rel. St. Dev. (data)	0.61	0.51	1.23	2.23	0.40	0.55	1.00
Contemp. Corr. with y (model)	1.00	-0.95	0.96	0.96	-0.67	-0.58	1.00
Contemp. Corr. with y(data)	0.88	0.38	0.60	0.73	0.18	0.12	1.00