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Assessing the empirical relevance of Walrasian labor frictions to business cycle fluctuations

João Madeira*

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Abstract

This paper describes and estimates (with a Bayesian likelihood approach) an otherwise standard dynamic stochastic general equilibrium model, with both sticky prices and wages, augmented with several labor market rigidities (of a Walrasian nature), namely: indivisible labor, predetermined straight time employment numbers (in which case, firms adjust overtime employment to respond to unexpected shocks), hiring expenses and convex adjustment costs. The results show all these frictions to be empirically important.

Labor frictions are shown to have important implications to business cycle dynamics and economic policy making. Labor frictions imply TFP shocks have a greater role in accounting for business cycle dynamics. Labor frictions also imply fiscal policy to lead to a greater crowding out of private sector activity and monetary policy to be more effective in achieving disinflation.

JEL Classification: E20, E24, E30, E31, E32.

Keywords: DSGE; New Keynesian, labor frictions; indivisible labor; labor adjustment costs; overtime; employment; hours.

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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 markets have deserved 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. Only a few labor market rigidities have been recently explored in the literature, mostly of a non-Walrasian nature. These include search and matching frictions of workers to jobs (Walsh, 2005, and Trigari, 2009), efficiency wages (Danthine and Kurmann, 2004), imperfect competition in labor supply and wage stickiness (Erceg, Henderson and Levin, 2000). Of these only the latter have become widely adopted by 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 its importance to improving the fit of DSGE models to the aggregate time series data still remains an open question (see Shimer, 2005, Krause and Lubik, 2007, Krause, Lopez-Salido and Lubik, 2008, and Lubik, 2009). Despite greater widespread use, the assumption of wage stickiness is also disputed (Smets and Wouters, 2007, and Gertler, Sala and Trigari, 2008, show positive evidence in favor of wage stickiness but Rabanal and Rubio-Ramírez, 2005, found it to not significantly improve the fit to the data and Krause and Lubik, 2007, found that inflation dynamics is only weakly affected by real wage rigidity).

In this paper I follow a different approach to labor market rigidities. I introduce Walrasian type labor frictions into an otherwise standard New Keynesian (NK) model (specifically, a DSGE model with both sticky prices and wages). In particular, I assume labor to be indivisible (labor cannot be supplied in 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), hiring expenses and convex labor adjustment costs.¹ The model is estimated with Bayesian methods and the same US time series data as Smets and Wouters (2007) but updated to include observations for the most recent years. Estimation results show a significant improvement in the fit to the data, proving all these frictions to be empirically important.

Walrasian labor frictions affect the model's dynamics considerably. Effects of TFP shocks are amplified due to costly adjustment of labor (which reduces the fall in hours from a positive TFP shock in a sticky price model). 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. Anti-inflationary monetary policy is shown to be achievable with a smaller interest rate increase by the central bank (this result is consistent with the empirical reduced form evidence of Batini, Jackson and Nickell, 2005, who found labor adjustment costs to be significant to estimates of the New Keynesian Phillips curve).

Prior studies showed that the Walrasian 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 Walrasian 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 such type of Walrasian 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, if anything the implications should be even more relevant; the interactions between economic policy making and Walrasian labor market rigidities should also be worth

¹The model allows for fluctuations in aggregate hours to be made along the intensive margin (that is, variation in hours per worker) and extensive margin (variation in number of workers). Standard New Keynesian models with no labor frictions (see for example Galí, 2008) allow only for fluctuations in aggregate hours made along the intensive margin while New Keynesian models with search and match frictions allow only for fluctuations along the extensive margin (for example: Walsh, 2005, and Trigari, 2009). In this aspect, the model considered here is more general than either approach.

exploring, since the examples of Keynes and Friedman showed the study of labor markets to be fruitful in this aspect in the past). 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 models

In the first subsection I describe the baseline model (M0) which consists of a DSGE model with Calvo price and wage stickiness which is extended to include a wide range of labor frictions (of a Walrasian nature): 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), firms also face hiring expenses and convex adjustment costs in changing the number of straight time workers.

The second subsection includes a description of several comparison models (M1, M2 and M3) in which the Walrasian labor frictions mentioned above are removed sequentially in order to later allow the assessment of the role of each to business cycle dynamics.

2.1 A New Keynesian model with labor frictions

2.1.1 Households

Consider an economy with a continuum of identical infinitely-lived agents on the interval $[0,1]$. Agents who have preferences over consumption of a single nondurable good C_t relative to a habit stock (assumed to depend on the level of technology η^t , which represents the labor-augmenting deterministic growth rate in the economy) and leisure L_t . The habit stock

assumption (which is similar to that in An and Schorfheide, 2007) ensures that the economy evolves along a balanced growth path even if the utility function is additively separable in consumption and leisure. The utility of each agent is

$$\sum_{s=0}^{\infty} \beta^s \left(\frac{1}{1-\sigma} \left(\frac{C_{t+s}}{\eta^{t+s}} \right)^{1-\sigma} + \varepsilon_{t+s}^l v \frac{1}{1-\chi} L_{t+s}^{1-\chi} \right) \quad (1)$$

where $0 < \beta < 1$ is the subjective discount factor, v is the utility from leisure (and has a value strictly greater than zero), σ is the inverse of the intertemporal elasticity of substitution and χ is the inverse elasticity of labor supply.

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

- T if the agent is unemployed;
- $T - t_1$ if the agent is employed but works the straight shift only;
- $T - t_1 - t_2$ if the agent works both the straight and overtime shift.

I employ lotteries to convexify the commodity space, following Hansen (1985) and Rogerson (1988). The end result is a similar utility specification (see the web appendix for details) to that used by Hansen and Sargent (1988) and Hall (1996)

$$\sum_{s=0}^{\infty} \beta^s \left[\frac{1}{1-\sigma} \left(\frac{C_{t+s}}{\eta^{t+s}} \right)^{1-\sigma} - \varepsilon_{t+s}^l a_1 (N_{1,t+s} - N_{2,t+s}) - \varepsilon_{t+s}^l a_2 N_{2,t+s} - \varepsilon_{t+s}^l a_0 (1 - N_{1,t+s}) \right], \quad (2)$$

where $a_0 \equiv -v \frac{1}{1-\chi} (1)^{1-\chi}$, $a_1 \equiv -v \frac{1}{1-\chi} (1 - h_1)^{1-\chi}$, $a_2 \equiv -v \frac{1}{1-\chi} (1 - h_1 - h_2)^{1-\chi}$, $h_1 = t_1/T$ and $h_2 = t_2/T$ (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 (straight time employment) and $N_{2,t}$ is the share of workers who work both shifts (overtime employment). This representative agent

maximizes (2) subject to the sequence of budget constraints given by

$$P_t(C_t + I_t + \Psi(u_t)K_t) + E_t \left\{ \frac{B_{t+1}}{\varepsilon_t^b R_t} \right\} = B_t + W_{1,t}h_1N_{1,t} + W_{2,t}h_2N_{2,t} + T_t + D_t + TR_t + R_t^k P_t u_t K_t + P_t(I_t - \varepsilon_t^i I(\frac{K_{t+1}}{K_t})K_t), \quad (3)$$

where P_t is the price of the final good, I_t represents investment expenditures, K_t is the stock of capital (which becomes productive with a one period delay), u_t is the degree of capital utilization, R_t^k corresponds to the real rental cost for capital services, B_t is the nominal payoff of a risk-less one period bond held at the end of period t , R_t denotes the gross nominal interest rate, $W_{1,t}$ is the nominal hourly wage of the straight shift, $W_{2,t}$ is the nominal hourly wage of the overtime shift, T_t denotes firms profits, D_t denotes profits from a perfectly competitive representative agency which matches workers with firms and TR_t are government transfers. The function $I(\cdot)$ is an increasing and convex function, of the usual kind assumed in neoclassical investment theory, which satisfies $I'(\eta) = 1$, $I(\eta) = \delta$, and $I''(\eta) = \epsilon_\psi$, δ is the depreciation rate and ϵ_ψ measures the convex capital adjustment costs in a log-linear approximation to the equilibrium dynamics. I assume that $\Psi(u_t)$ 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 $u = 1$ and $\Psi(1) = 0$. To solve the model, one needs only the inverse of the elasticity of the capital utilization cost function: $\Psi'(1)/\Psi''(1) = (1 - \Psi)/\Psi$.

The resulting first-order conditions (FOC) are

$$\frac{1}{\varepsilon_t^b R_t} = \beta E_t \left\{ \left(\frac{C_{t+1}/\eta^{t+1}}{C_t/\eta^t} \right)^{-\sigma} (\eta^t/\eta^{t+1})(P_t/P_{t+1}) \right\}, \quad (4)$$

$$\frac{W_{1,t}/\eta^t}{P_t} h_1 \left(\frac{C_t}{\eta^t} \right)^{-\sigma} = (a_1 - a_0) \varepsilon_t^l, \quad (5)$$

$$\frac{W_{2,t}/\eta^t}{P_t} h_2 \left(\frac{C_t}{\eta^t} \right)^{-\sigma} = (a_2 - a_1) \varepsilon_t^l. \quad (6)$$

$$\varepsilon_t^i I'(\frac{K_{t+1}}{K_t}) = E_t \beta \tilde{\Lambda}_{t,1} [R_{t+1}^k u_{t+1} - \Psi(u_{t+1}) + \frac{K_{t+2}}{K_{t+1}} \varepsilon_{t+1}^i I'(\frac{K_{t+2}}{K_{t+1}}) - \varepsilon_{t+1}^i I(\frac{K_{t+2}}{K_{t+1}})], \quad (7)$$

$$R_t^k = \Psi'(u_t), \quad (8)$$

where $\Lambda_{t,j} = (C_{t+j}/C_t)^{-\sigma}$. These equations contain several stochastic shocks, which are assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + u_t^b$, $\varepsilon_t^l = \rho_l \varepsilon_{t-1}^l + u_t^l$ and $\varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + u_t^i$. ε_t^b represents a wedge between the central bank interest rate and the return on assets owned by households, ε_t^l represents a shock to the labor supply and finally ε_t^i is a shock to the convex capital adjustment cost function.

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:

$$\sum_{j=0}^{\infty} E_t \frac{P_t}{P_{t+j}} \beta^j \Lambda_{t,j} (\rho_{t+j} P_{t+j} N_{1,t+j} - P_{t+j} H_{t+j}) \quad (9)$$

subject to:

$$H_t = \eta^t H(\frac{N_{1,t+1}}{N_{1,t}}) N_{1,t}, \quad (10)$$

where H_t represent purchases by the agency of the final good and ρ_t corresponds to the real price per period charged by the agency to firms per unit of straight time employment ($N_{1,t}$). The function $H(\cdot)$ is an increasing and convex function, of similar form to $I(\cdot)$, which satisfies $H(1) = \delta_{N1}$, $H'(1) = \Theta$ and $H''(1) = \epsilon_{\psi N1}$. In the baseline model I will assume $\Theta = 1$ which implies the presence of hiring expenses (these could be viewed as resulting from advertising, screening, administrative or training costs related to the entry of new workers). The convexity of $H(\cdot)$ implies the existence of costs of adjustment, with $\epsilon_{\psi N1}$ measuring the degree of labor adjustment costs (these could be viewed as resulting from disruptions to production from changing the number of employees). The parameter δ_{N1} can be interpreted as the exogenous quit rate in employment.

The resulting first-order condition is given by:

$$\eta^t H'(\frac{N_{1,t+1}}{N_{1,t}}) = E_t \beta \Lambda_{t,1} [\rho_{t+1} + \frac{N_{1,t+2}}{N_{1,t+1}} \eta^{t+1} H'(\frac{N_{1,t+2}}{N_{1,t+1}}) - \eta^{t+1} H(\frac{N_{1,t+2}}{N_{1,t+1}})]. \quad (11)$$

2.1.2 Wage Setting Decision

As in Smets and Wouters (2003) I assume a continuum of monopolistically competitive households (indexed on the unit interval), each of which supplies a differentiated labor service. Households' labor hours are aggregated using a Dixit-Stiglitz technology:

$$N_{z,t} = [\int_0^1 N_{z,t}^{\frac{(\epsilon_w-1)}{\epsilon_w}}(i) di]^{\frac{\epsilon_w}{(\epsilon_w-1)}} \quad (12)$$

with $z \in \{1, 2\}$. Due to the non-stationary technology process, it is convenient to express the model in terms of the detrended variables $\tilde{Y}_t = (Y_t/\eta^t)$, $\tilde{W}_{1,t} = (W_{1,t}/\eta^t)$, $\tilde{W}_{2,t} = (W_{2,t}/\eta^t)$, $\tilde{C}_t = (C_t/\eta^t)$, $\tilde{I}_t = (I_t/\eta^t)$, $\tilde{K}_t = (K_t/\eta^t)$ and $\tilde{H}_t = (H_t/\eta^t)$.

Total demand for household i 's labor is:

$$N_{z,t} = \left[\frac{\tilde{W}_{z,t}(i)}{\tilde{W}_{z,t}} \right]^{-\epsilon_w} N_{z,t} \quad (13)$$

where $\tilde{W}_{z,t}$ is the price index cost of $N_{z,t}$:

$$\tilde{W}_{z,t} = [\int_0^1 \tilde{W}_{z,t}^{(1-\epsilon_w)}(i) di]^{\frac{1}{(1-\epsilon_w)}} \quad (14)$$

The household union takes labor demand into account when setting wages. Nominal wages are set in staggered contracts. In particular, a constant fraction $(1 - \theta_w)$ of households renegotiate their wage contracts in each period. When given the chance, household unions will set wages as a mark-up over the marginal rate of substitution of leisure for consumption. The parameter ϵ_w defines the steady state wage markup as $1 + \lambda_w = \frac{1}{1-1/\epsilon_w}$. The household union maximization problem is:

$$E_t \sum_{j=0}^{\infty} (\beta \theta_w)^j \tilde{\Lambda}_{t,j} \left\{ \frac{\tilde{W}_{z,t}(i) - MRS_{z,t+j}^n}{P_{t+j}} N_{z,t,t+j}(i) \right\} \quad (15)$$

s.t.

$$N_{z,t,t+j}(i) = \left[\frac{\tilde{W}_{z,t}(i)}{\tilde{W}_{z,t+j}} \right]^{-\epsilon_w} N_{z,t+j} \quad (16)$$

where $MRS_{1,t}^n = P_t \tilde{C}_t^\sigma \varepsilon_t^l (a_1 - a_0) / h_1$, $MRS_{2,t}^n = P_t \tilde{C}_t^\sigma \varepsilon_t^l (a_2 - a_1) / h_2$ and $\tilde{\Lambda}_{t,j} = \eta^{-\sigma} (\tilde{C}_{t+j} / \tilde{C}_t)^{-\sigma}$. The household union takes as given the paths of $MRS_{z,t+j}^n$, P_{t+j} , $\tilde{W}_{z,t+j}$ and $N_{z,t+j}$. The first order condition with respect to $\tilde{W}_{z,t}(i)$ is:

$$E_t \sum_{j=0}^{\infty} (\beta \theta_w)^j \tilde{\Lambda}_{t,j} \left\{ \frac{N_{z,t,t+j}(i)}{P_{t+j}} - \epsilon_w \frac{1}{\tilde{W}_{z,t+j}} \frac{\tilde{W}_{z,t}(i) - MRS_{z,t+j}^n}{P_{t+j}} N_{z,t,t+j}(i) \left[\frac{\tilde{W}_{z,t}(i)}{\tilde{W}_{z,t+j}} \right]^{-1} \right\} = 0 \quad (17)$$

2.1.3 Firms

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

$$Y_t = \left[\int_0^1 Y_t^{1/(1+\lambda_{p,t})}(i) di \right]^{1+\lambda_{p,t}}, \quad (18)$$

where the time-varying mark-up in the goods market $\lambda_{p,t}$ is determined by the following stochastic process: $\log \lambda_{p,t} = (1 - \rho_p) \log \lambda_p + \rho_p \log \lambda_{p,t-1} - \mu_p u_{t-1}^p + u_t^p$. The price mark-up shock, u_t^p , is IID- Normal of mean zero and standard deviation σ_p . Profit maximization leads to the following demand for the i^{th} good:

$$Y_t(i) = (P_t / P_t(i))^{(1+\lambda_{p,t})/\lambda_{p,t}} Y_t, \quad (19)$$

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

$$P_t = \left[\int_0^1 P_t^{-1/\lambda_{p,t}}(i) di \right]^{-\lambda_{p,t}}. \quad (20)$$

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

$$Y_t(i) = A_t(\eta^t)^{1-\alpha} \bar{K}_t^\alpha(i) [h_1 N_{1,t}^{1-\alpha}(i) + h_2 N_{2,t}^{1-\alpha}(i)], \quad (21)$$

where $\bar{K}_t = u_t K_t$ is effective capital and A_t is total factor productivity (TFP) which follows the process: $\ln(A_t) = (1 - \rho_a) \ln(A) + \rho_a \ln(A_{t-1}) + u_t^a$ with u_t^a representing an independent shock with normal distribution of mean zero and standard deviation σ_a . Hansen and Sargent (1988) and Hall (1996) use a similar production function.² The firm's labor input is given by:

$$N_t(i) = h_1 N_{1,t}(i) + h_2 N_{2,t}(i). \quad (22)$$

To maximize profit the i^{th} intermediate good firm chooses $P_t(i)$, $Y_{t+j}(i)$, $\bar{K}_t(i)$, $N_{1,t+j}(i)$, $N_{2,t+j}(i)$ subject to (19) and (21). Intermediate good firms face Calvo price staggering and take P_{t+j} , Y_{t+j} , R_{t+j}^k , $W_{1,t+j}$ and $W_{2,t+j}$ as given. The i^{th} intermediate good firm maximization problem is:

$$\sum_{j=0}^{\infty} (\theta\beta)^j E_t \left\{ \frac{P_t}{P_{t+j}} \Lambda_{t,j} [P_t(i) Y_{t+j}(i) - (\rho_{t+j} P_{t+j} + W_{1,t+j} h_1) N_{1,t+j}(i) - W_{2,t+j} h_2 N_{2,t+j}(i) - R_{t+j}^k P_{t+j} \bar{K}_{t+j}(i)] \right\} = 0, \quad (23)$$

where θ is the probability the firm will not be able to optimally reset its price in a given period. The resulting first-order conditions are:

$$E_t \sum_{j=0}^{\infty} (\theta\beta)^j \Lambda_{t,j} \frac{P_{t+j}}{P_{t+j+1}} Y_{t+j}(i) [P_t(i) - (1 + \lambda_{p,t+j}) MC_{t+j}(i)] = 0, \quad (24)$$

²This “shift work” production function was first developed by Lucas (1970) who showed it matched better observed cyclical patterns in production and real wages than the standard neoclassical and the fixed factor proportions production functions.

$$\frac{\rho_t + \frac{W_{1,t}}{P_t} h_1}{(1 - \alpha) A_t (\eta^t)^{1-\alpha} \bar{K}_t^\alpha(i) h_1 N_{1,t}^{-\alpha}(i)} = MC_t(i). \quad (25)$$

$$\frac{W_{2,t}/P_t}{(1 - \alpha) A_t (\eta^t)^{1-\alpha} \bar{K}_t^\alpha(i) N_{2,t}^{-\alpha}(i)} = MC_t(i), \quad (26)$$

$$\frac{R_t^k \bar{K}_t(i)}{\alpha Y_t(i)} = MC_t(i), \quad (27)$$

where $MC_t(i)$ denotes the Lagrange multiplier of the production function constraint (which is commonly interpreted as the firm's real marginal cost).

2.1.4 Market clearing and monetary policy rule

The aggregate economy's resource constraint is:

$$Y_t = C_t + I_t + G_t + \Psi(u_t) K_t + H_t \quad (28)$$

where G_t stands for government expenditures. Detrended government expenses ($\tilde{G}_t = G_t/\eta^t$) are exogenous and assumed to follow the process: $\ln(\tilde{G}_t) = (1 - \rho_g) \ln(\tilde{G}) + \rho_g \ln(\tilde{G}_{t-1}) + u_t^g$ with u_t^g representing an independent shock normally distributed with mean zero and standard deviation σ_g . I assume that government adjusts lump sum taxes ($-TR_t$) to ensure that its intertemporal budget constraint holds.

The model is closed by assuming the central bank follows an interest rate rule according to (from now on, I will use lower case letters to denote variables in log deviation from the steady state)

$$r_t = \rho_r r_{t-1} + (1 - \rho_r) \gamma_\pi (\pi_t) + (1 - \rho_r) \gamma_y \tilde{y}_t^* + (1 - \rho_r) \gamma_{\Delta y} (\tilde{y}_t^* - \tilde{y}_{t-1}^*) + u_t^r \quad (29)$$

where $\pi_t = p_t - p_{t-1}$ is inflation and $\tilde{y}_t^* = \tilde{y}_t - \tilde{y}_t^f$, the *output gap*, is the log deviation of output from its flexible price and wages counterpart (potential output). This is the same monetary policy rule adopted by Smets and Wouters (2007). Finally, the monetary policy

shock u_t^r is a zero mean white noise process.

2.2 Comparison models

Comparison model 1 (M1) is identical to the baseline model but $N_{1,t}$ is no longer assumed to be predetermined; in this model the function $H(\cdot)$ is given by:

$$H_t = \eta^t H\left(\frac{N_{1,t}}{N_{1,t-1}}\right) N_{1,t-1}, \quad (30)$$

The resulting first-order condition of the agency with respect to $N_{1,t}$ is given by:

$$\eta^t H'\left(\frac{N_{1,t}}{N_{1,t-1}}\right) = \rho_t + E_t \beta \Lambda_{t,1} \left[\frac{N_{1,t+1}}{N_{1,t}} \eta^{t+1} H'\left(\frac{N_{1,t+1}}{N_{1,t}}\right) - \eta^{t+1} H\left(\frac{N_{1,t+1}}{N_{1,t}}\right) \right]. \quad (31)$$

which replaces equation (11).

Comparison model 2 (M2) is identical to comparison model 2 but with no hiring and labor adjustment costs ($\delta_{N1} = \Theta = \epsilon_{\psi N1} = 0$). In this case $N_{2,t}$ becomes a constant multiple of $N_{1,t}$. The model essentially becomes reduced to a simple indivisible labor model with no relevant cyclical distinction between overtime and straight time employment.

Comparison model 3 (M3) consists of a very conventional New Keynesian model where labor is neither indivisible (that is, in this model $L_t = 1 - N_t$) or predetermined (and there are no hiring or labor adjustment costs). In this model household's maximize (1) subject to:

$$P_t(C_t + I_t + \Psi(u_t)K_t) + E_t \left\{ \frac{B_{t+1}}{\varepsilon_t^b R_t} \right\} = B_t + W_t N_t + T_t + T R_t + R_t^k P_t u_t K_t + P_t (I_t - \varepsilon_t^i I(\frac{K_{t+1}}{K_t}) K_t), \quad (32)$$

The resulting FOC are given by (4), (7), (8) and:

$$\left(\frac{C_t}{\eta^t}\right)^{-\sigma} \frac{W_t/\eta^t}{P_t} = \varepsilon_t^l v(1 - N_t)^{-\chi}. \quad (33)$$

In the wage setting decision (17) one therefore has $N_{z,t} = N_t$, $W_{z,t} = W_t$ and $MRS_{z,t}^n =$

$MRS_t^n = P_t \tilde{C}_t^\sigma \varepsilon_t^l v(1 - N_t)^{-\chi}$. The production function is now given by:

$$Y_t(i) = A_t(\eta^t)^{1-\alpha} \bar{K}_t^\alpha(i) N_t^{1-\alpha}(i). \quad (34)$$

The i^{th} intermediate good firm now chooses $P_t(i)$, $Y_{t+j}(i)$, $\bar{K}_t(i)$, $N_{t+j}(i)$ to maximize the following profit function subject to (19) and (34):

$$\sum_{j=0}^{\infty} (\theta\beta)^j E_t \left\{ \frac{P_t}{P_{t+j}} \Lambda_{t,j} [P_t(i) Y_{t+j}(i) - W_{t+j} N_{t+j}(i) - R_{t+j}^k P_{t+j} \bar{K}_{t+j}(i)] \right\}. \quad (35)$$

The resulting FOC are given by (24), (27) and:

$$\frac{W_t/P_t}{(1-\alpha)A_t(\eta^t)^{1-\alpha} \bar{K}_t^\alpha(i) N_t^{1-\alpha}(i)} = MC_t(i). \quad (36)$$

3 Model Estimation

3.1 Estimation Methodology

I adopt a Bayesian estimation methodology for the models presented in section 2 similar to that of Smets and Wouters (2007).³ 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.⁴ The log data density values of the models were obtained by modified harmonic mean estimation.

The dataset used consists of the same 7 seasonally adjusted quarterly US aggregate time series as in Smets and Wouters (2007) but updated to include observations for more recent years (the models are estimated for the period 1966Q1 to 2012Q4): 100 times the

³This was implemented with the use of Dynare (freely available at www.dynare.org).

⁴The procedure adopted was the same as in Smets and Wouters (2007) apart from the value of the scale used for the jumping distribution in Metropolis-Hastings algorithm. Smets and Wouters (2007) used a value of 0.3 whereas I used values between 0.34 and 0.44 (depending on the model) in order to yield an acceptance rate of approximately 23%, the optimal rate proposed by Gelman et al. (1996).

log difference of the GDP deflator, real consumption, real investment, real wages and real GDP, 100 times the log of average hours worked (for the NFB sector for all persons) and the federal funds rate.⁵

The corresponding measurement equations are:

$$\begin{bmatrix} dlGDP_t \\ dlCONS_t \\ dlINV_t \\ dlWAG_t \\ lHOURS_t \\ dlP_t \\ FEDFUNDS_t \end{bmatrix} = \begin{bmatrix} \bar{\lambda} \\ \bar{\lambda} \\ \bar{\lambda} \\ \bar{\lambda} \\ \bar{n} \\ \bar{\pi} \\ \bar{r} \end{bmatrix} + \begin{bmatrix} \tilde{y}_t - \tilde{y}_{t-1} \\ \tilde{c}_t - \tilde{c}_{t-1} \\ \tilde{i}_t - \tilde{i}_{t-1} \\ \tilde{w}_t - \tilde{w}_{t-1} \\ n_t \\ \pi_t \\ r_t \end{bmatrix}, \quad (37)$$

where l and dl stand respectively for log and log difference, $\bar{\lambda}$ is the common quarterly trend growth rate to real GDP, consumption, investment and wages, \bar{n} is the average of the log of hours worked (which is normalized to be equal to zero), $\bar{\pi}$ and \bar{r} are the average values of inflation and interest rate. The parameters $\bar{\lambda}$, $\bar{\pi}$ and \bar{r} are related to the steady states of the model economy as follows: $\eta = 1 + \frac{\bar{\lambda}}{100}$ and $\beta = \frac{1+\bar{\pi}/100}{1+\bar{r}/100}\eta$.

3.2 Prior Distribution of the Parameters

The choice of prior distribution for the model's parameters is for the most part similar to Smets and Wouters (2007). Not all parameters were estimated, namely: δ is set at 0.025, the exogenous spending-GDP ratio is fixed at 20% (the average of the share of federal government expenses in the US), the steady-state mark-ups λ_p and λ_w are respectively set at 0.15 (as in Woodford, 2005) and 0.5. As in King and Rebelo (2000), χ is assumed to be 1 and the leisure utility parameter v is set at 3.48.

The mean prior quit rate in employment (δ_{N1}) is chosen to be 0.1 (consistent with the

⁵I also estimated the models for the period 1966Q1 to 2007Q4 (as in Galí et al., 2011). The results are robust to the choice of sample period (see the web appendix).

empirical evidence for the U.S., see Shimer, 2005). The mean prior of the normalized straight time shift (h_1) is assumed to be 0.38, while the prior mean of the normalized overtime shift (h_2) is 0.11.⁶ The priors for these parameters are all assumed to follow a normal distribution with 0.05 standard deviation.

As in Neri (2004) the prior on the adjustment cost parameter for capital is assumed to follow a gamma distribution with 15 and standard deviation of 5. I use the same prior for the curvature on labor adjustment costs.⁷ The priors for the remaining parameters are the same as in Smets and Wouters (2007).

The second and sixth columns of table 1 give an overview of the assumptions made regarding the prior distribution (shape, mean and standard deviation) of all estimated parameters.

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), of the baseline model (M0). The results are displayed in table 1. With respect to the comparison models (M1, M2 and M3) I report (in table 2) only, to save space, the mean of the posterior distribution of the estimated parameters.

Parameter estimates for all models 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 Walrasian type labor frictions. Most noticeably of all is the parameter

⁶The prior means for h_1 and h_2 are consistent with setting the agents time endowment (T) at 1369 hours per quarter (implying agent's have 15 hours per day available for work and leisure activities, this is the same value as in Hall, 1996, and Burnside, Eichenbaum and Rebelo, 1993), the straight time shift (t_1) at 516 hours per quarter (40 hours a week) and the overtime shift (t_2) to be equal to 155 hours per quarter (the implied time series mean of overtime hours, when one assumes the straight time shift to be 40 hours per week, for details see Madeira, 2012).

⁷The choice of prior of the capital adjustment cost in Neri (2004) is based on Ireland's estimates (see table 2 in Ireland, 2004). I adopted the same prior for the labor adjustment cost parameter for the following reason: Shapiro (1986) estimate, using macro data, is a value close to 0 while Chang, Doh and Schorfheide (2007) use a prior of 33 based on the average recruiting cost of workers (and obtain a posterior mean estimate around 11). A value of 15 is within the mid range of these values and therefore seemed a reasonable choice for labor adjustment costs as well.

measuring the degree of capital adjustment costs, ϵ_ψ . In the baseline model (M0) which includes all the labor frictions, the parameter estimate is 15.95; this estimate increases in value whenever some type of Walrasian labor friction is removed. In the model which includes no Walrasian type labor frictions (M3) the estimated value is 28.62. The absence of Walrasian labor frictions results in an upward bias of estimates of ϵ_ψ (something similar happens with the curvature on labor adjustment costs, $\epsilon_{\psi N1}$, in the baseline model the mean posterior estimate is 26.58 but when the assumption of predetermined $N_{1,t}$ is removed this estimate increases to 29.86). Another parameter, whose posterior mean estimate, is altered, when Walrasian labor frictions are added, is the intertemporal elasticity of substitution. Consumption becomes less sensitive to interest rates when hiring and labor adjustment costs are not present. The capital share, α , is estimated to be much higher in the models with indivisible labor. This is a positive outcome, as with indivisible labor the value becomes much closer to what has been adopted in the literature (for example, King and Rebelo, 2000, choose a value of 1/3 for the capital share) and implies an estimate of the long run US labor income share around 0.7 which is in line with the data (for a discussion, see Cooley and Prescott, 1995). The Calvo wage stickiness probability of nonadjustment, θ_w , seems to be slightly reduced with the introduction of other Walrasian labor frictions. Therefore abstracting from Walrasian labor frictions leads to an overstatement of the degree of wage stickiness in New Keynesian models. Estimates of the monetary policy rule appear to be stable across models.

With respect to the estimates of the exogenous shocks parameters the AR(1) coefficients are estimated to be quite high with values equal or higher than 0.9 for most shocks in all the models. Introducing Walrasian type labor frictions seems to reduce the estimated values of ρ_a , ρ_b and ρ_g to a significant degree (while implying an increase of the estimate of the degree of autocorrelation, ρ_p , of the price mark-up shock). The estimated volatilities of the shock processes are also for the most part unaffected. Mean estimates of σ_a and σ_l increase in the models with Walrasian labor frictions while σ_i diminishes very significantly in value whenever some type of Walrasian labor friction is introduced.

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 tables 1 and 2. The log marginal likelihood of the baseline model (M0) is -1309.43 which is higher than that of any of the comparison models (M1, M2 and M3). This suggests that Walrasian type 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. Values between 6 and 10 represent strong evidence, between 2 and 6 positive evidence, while values below 2 are "not worth more than a bare mention".

When I consider the baseline model (M0) against comparison model 1 (M1) I obtain a KR criterion of 9.74. Since M1 is identical to M0 but absent predetermined straight time employment ($N_{1,t}$), the evidence is therefore strong in favor of the assumption of predetermined employment. When one compares comparison model 1 against comparison model 2 (M2), which is identical to M1 but with no hiring and convex labor adjustment costs, the KR criterion is 25.38. The KR criterion therefore conclusively supports the importance of hiring and labor adjustment costs for the understanding of business cycle fluctuations. Finally, the KR value of comparison model 2 against comparison model 3 (M3), which is identical to M3 but with no indivisible labor, is 33.26. So, there is also very strong evidence in favor of the assumption of indivisible labor.

4.2 Variance Decomposition

Table 3 displays the forecast error variance decomposition at a 20 quarter horizon (King and Rebelo, 2000, consider business cycles to be periods 'between 6 and 32 quarters', 20 quarters

is approximately the midpoint of this interval) for output (\tilde{y}_t) and inflation (π_t).

Walrasian labor frictions do appear to have a significant impact on the analysis of the driving forces of output. The introduction of Walrasian type labor frictions increases the importance of total factor productivity (accounting for about 22% share of output volatility in M0 in comparison with just 12% under M3) and price mark-up shocks (representing 15% share of output volatility in M0 while just 6% in M3) while substantially reducing the relevance of fiscal shocks (11% share of output volatility in M0 while accounting as much as 28% in the model with no Walrasian labor frictions, M3) to the understanding of business cycle fluctuations.

Walrasian labor frictions also seem to be important in understanding inflation dynamics. Just as with output, price mark-up shocks also increase in importance (representing 50% share of inflation volatility in M0 while just 31% in M3). This is compensated by a smaller role of the risk premium (representing 12% share of inflation volatility in M0 while 32% in M3) and labor supply shocks (representing 22% share of inflation volatility in M0 while 34% in M3) in accounting for inflation movements in Walrasian labor frictions models. Similarly to output, the introduction of labor frictions of a Walrasian nature increases the importance of total factor productivity (accounting for about 2% share of inflation volatility in M0 in comparison with about 0% under M3). However, unlike with output, fiscal shocks explain a greater fraction of inflation fluctuations in models with hiring expenses and labor adjustment costs (representing 2% share of inflation volatility in M0 while close to 0% in M2 and M3). Also noteworthy is the increased role of monetary policy in accounting for inflation movements with the introduction of Walrasian type labor frictions (representing about 7% share of inflation volatility in M0, 5% in M1, 3% M2 and 2% in M3).

4.3 Impulse Response Functions

Figures 1-7 display the impulse response functions (IRFs) of key economic variables (output, consumption, investment, hours, straight time employment, overtime employment, wages, interest rate and inflation) of all models to exogenous shocks (the figures are normalized in

percentage of the standard error of each shock).

Figure 1 shows that the introduction of hiring expenses and labor adjustment costs amplifies considerably the effects of TFP shocks. Output, consumption and investment increase by more while inflation and interest rates fall by more. This happens because the reduction in hours from the TFP shock is less (because adjustment is more costly) than in the absence of hiring expenses and labor adjustment costs. Since hours are clearly procyclical in the data, some have argued that the New Keynesian model is not compatible with a large role for TFP shocks in explaining business cycles.⁸ The introduction of hiring expenses and labor adjustment costs allows TFP shocks to play a larger role in accounting for observed cyclical movements in economic variables.

Figure 2 shows that the introduction of Walrasian labor frictions diminishes the effects of an increase in the risk premium. Again, this happens because it is more costly to reduce the labor input and therefore output falls by less.

In figure 3 one sees the impulse response functions of the models to an 1% increase in government spending. Costly adjustment of labor implies a smaller output increase in response to an unexpected fiscal expansion shock. Again, this happens because of a dampened reaction in hours. Figure 3 shows that Walrasian type labor frictions result in greater crowding out of consumption and investment to fiscal expansion. This can be explained not just due to the smaller increase in hours but also by a lower estimate of the inverse of the intertemporal elasticity of substitution σ when Walrasian labor frictions are introduced.

Figure 4 presents the IRFs of the models to an exogenous increase in interest rate by the central bank. Inflation, falls by more in models with Walrasian labor frictions. This is due to the fact that straight time employment is costly to adjust and this is reflected in the firm's real marginal cost, as shown in (25). In model's with costs of rapidly changing straight time employment, real marginal costs fall not just due to the fall in wages but also due to a fall in the real price (ρ_t) paid per unit of straight time employment by firms to the rental agency. An alternative way, to interpret the finding, of sharper fall in inflation

⁸A debate sparked mostly by the work of Galí (1999) who using a structural VAR found a short run fall of hours worked in response to a positive technology shock.

in Walrasian labor friction models, is to think of real marginal costs determined in terms of overtime employment, as shown in (26). When straight time employment is costly to adjust then, to compensate for this, firms respond by making large changes in terms of overtime employment. This means that in model's with Walrasian labor frictions there is a greater reduction of overtime employment (as can be confirmed in figure 4) in response to an interest rate increase by the central bank. This implies that real marginal costs fall by more in the estimated models with labor frictions of a Walrasian nature and so does inflation since it is a function of the present value of future real marginal costs. This has important consequences for monetary policy since it shows that abstracting from Walrasian labor frictions understates its true effectiveness in achieving disinflation. Notice also that even though the exogenous component increase, u_t^r , is the same in all models, the nominal interest rate is smaller whenever a Walrasian labor friction is introduced because given the same interest rate increase the resulting effect on output is smaller (because costly adjustment of labor makes firms cut hours by less resulting in a smaller fall in output) while it is larger for inflation.

The impulse response functions of the investment specific technology shock are displayed in figure 5, which shows that in the model with no Walrasian labor frictions the consequences of an increase in the cost of capital goods are less severe (in particular, smaller fall in output and investment). This is likely due to the fact that capital adjustment costs are estimated to be much higher in this model (therefore investment falls by less and consecutively so does output).

Figure 6 shows that the responses of economic variables to price mark-up shock become more persistent in the models with more labor frictions. One of the likely reasons for this is the greater estimated degree of autocorrelation (ρ_p) in those models.

Finally, figure 7 shows the dynamic consequences of a labor supply shock (also frequently labelled as a "wage mark-up" shock). As with the risk premium, fiscal and monetary policy shocks the introductions of Walrasian labor frictions diminishes the response of hours resulting in smaller reactions to the shock of other variables as well.

5 Conclusion

This paper presents a New Keynesian model with a wide range of labor frictions (of a Walrasian kind): indivisible labor, predetermined straight time employment numbers, hiring expenses and labor adjustment costs. All of which are proven empirically important, as shown by significant improvements of the log marginal likelihood. Walrasian labor frictions affect the model's dynamics substantially. Costly labor adjustment mitigates the fall in hours from positive TFP shocks and therefore amplifies the role of such shocks in accounting for cyclical output movements. This paper also has important policy implications. Fiscal policy is shown to imply a greater crowding out of consumption and investment expenses under models with Walrasian type labor frictions. This suggests that an important topic for future research is to examine the consequences of Walrasian labor frictions to fiscal multipliers at the zero lower bound. Monetary policy on the other hand is found to achieve disinflation more effectively under models with Walrasian labor frictions, indicating these should be relevant for research into optimal monetary policy.

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6 Tables

Table 1: Baseline Model Estimation (M0)

Prior Distribution		Posterior Dist.		Prior Distribution		Posterior Dist.	
Structural Parameters		Mean	St. Dev.	Shock Parameters		Mean	St. Dev.
$\bar{\lambda}$	$N(0.4, 0.1)$	0.41	0.02	σ_a	$IG(0.1, 2)$	0.69	0.04
$100(\beta^{-1} - 1)$	$G(0.25, 0.1)$	0.25	0.09	σ_b	$IG(0.1, 2)$	0.23	0.02
$\bar{\pi}$	$G(0.625, 0.1)$	0.77	0.06	σ_g	$IG(0.1, 2)$	2.94	0.16
\bar{n}	$N(0, 1)$	0.57	0.82	σ_i	$IG(0.1, 2)$	2.74	0.42
σ	$N(1.5, 0.375)$	1.48	0.17	σ_r	$IG(0.1, 2)$	0.29	0.02
h_1	$N(0.38, 0.05)$	0.56	0.04	σ_p	$IG(0.1, 2)$	0.16	0.02
h_2	$N(0.11, 0.05)$	0.14	0.03	σ_l	$IG(0.1, 2)$	0.74	0.09
Ψ	$B(0.5, 0.15)$	0.84	0.06				
ϵ_ψ	$G(15, 5)$	15.95	2.03	ρ_a	$B(0.5, 0.2)$	0.96	0.01
δ_{N1}	$N(0.1, 0.05)$	0.20	0.04	ρ_b	$B(0.5, 0.2)$	0.87	0.04
$\epsilon_{\psi N1}$	$G(15, 5)$	26.58	6.25	ρ_g	$B(0.5, 0.2)$	0.95	0.01
α	$N(0.3, 0.05)$	0.27	0.03	ρ_i	$B(0.5, 0.2)$	0.98	0.01
θ	$B(0.75, 0.1)$	0.88	0.05	ρ_l	$B(0.5, 0.2)$	0.95	0.01
θ_w	$B(0.5, 0.1)$	0.54	0.03	ρ_p	$B(0.5, 0.2)$	0.89	0.05
ρ_r	$B(0.75, 0.1)$	0.79	0.03	μ_p	$B(0.5, 0.2)$	0.69	0.07
γ_π	$N(1.5, 0.25)$	2.07	0.19				
γ_y	$N(0.125, 0.1)$	0.15	0.04				
$\gamma_{\Delta y}$	$N(0.125, 0.1)$	0.32	0.04				

Log data density (modified harmonic mean)

-1309.43

where $N(\gamma, \epsilon)$, $G(\gamma, \epsilon)$, $IG(\gamma, \epsilon)$ and $B(\gamma, \epsilon)$ correspond respectively to the normal, gamma, inverted gamma and beta distributions with mean γ and ϵ standard deviation.

Table 2: Mean Parameter Estimates of Comparison Models

	M1	M2	M3		M1	M2	M3
$\bar{\lambda}$	0.42	0.45	0.46	σ_a	0.70	0.72	0.65
$100(\beta^{-1} - 1)$	0.25	0.25	0.25	σ_b	0.22	0.19	0.19
$\bar{\pi}$	0.77	0.60	1.00	σ_g	2.97	3.13	3.08
\bar{n}	0.51	0.02	0.38	σ_i	3.06	4.82	7.65
σ	1.58	2.08	2.02	σ_r	0.30	0.31	0.28
h_1	0.57	0.63	-	σ_p	0.15	0.15	0.16
h_2	0.17	0.23	-	σ_l	0.75	0.63	0.57
Ψ	0.82	0.64	0.82				
ϵ_ψ	17.54	25.48	28.62	ρ_a	0.96	0.97	0.99
δ_{N1}	0.21	-	-	ρ_b	0.88	0.95	0.94
$\epsilon_{\psi N1}$	29.86	-	-	ρ_g	0.95	0.97	0.97
α	0.27	0.28	0.05	ρ_i	0.98	0.97	0.98
θ	0.89	0.91	0.91	ρ_l	0.95	0.95	0.95
θ_w	0.54	0.60	0.63	ρ_p	0.89	0.90	0.82
ρ_r	0.80	0.81	0.79	μ_p	0.70	0.74	0.63
γ_π	2.05	2.10	1.98				
γ_y	0.14	0.09	0.16				
$\gamma_{\Delta y}$	0.31	0.25	0.35				

Log data density (modified harmonic mean) -1314.30 -1326.99 -1343.62
where $N(\gamma, \epsilon)$, $G(\gamma, \epsilon)$, $IG(\gamma, \epsilon)$ and $B(\gamma, \epsilon)$ correspond respectively to the normal, gamma, inverted gamma and beta distributions with mean γ and ϵ standard deviation.

Table 3: Variance Decomposition (in percentage) 20 quarter horizon

Output (\tilde{y}_t)							
	u_t^a	u_t^b	u_t^g	u_t^i	u_t^r	u_t^p	u_t^l
M0	22.16	5.82	11.21	17.69	5.25	14.52	23.34
M1	18.83	7.55	13.95	19.28	6.30	12.72	21.36
M2	8.13	10.64	26.59	20.21	6.46	12.99	14.98
M3	11.73	9.89	28.49	13.62	4.30	5.84	26.13
Inflation (π_t)							
	u_t^a	u_t^b	u_t^g	u_t^i	u_t^r	u_t^p	u_t^l
M0	2.16	12.41	1.65	4.95	6.61	49.99	22.23
M1	2.12	12.23	1.07	3.77	4.95	52.24	23.61
M2	1.22	34.51	0.03	1.31	2.73	37.49	22.70
M3	0.35	32.37	0.05	0.30	1.68	31.03	34.21

7 Figures

Figure 1: Productivity shock

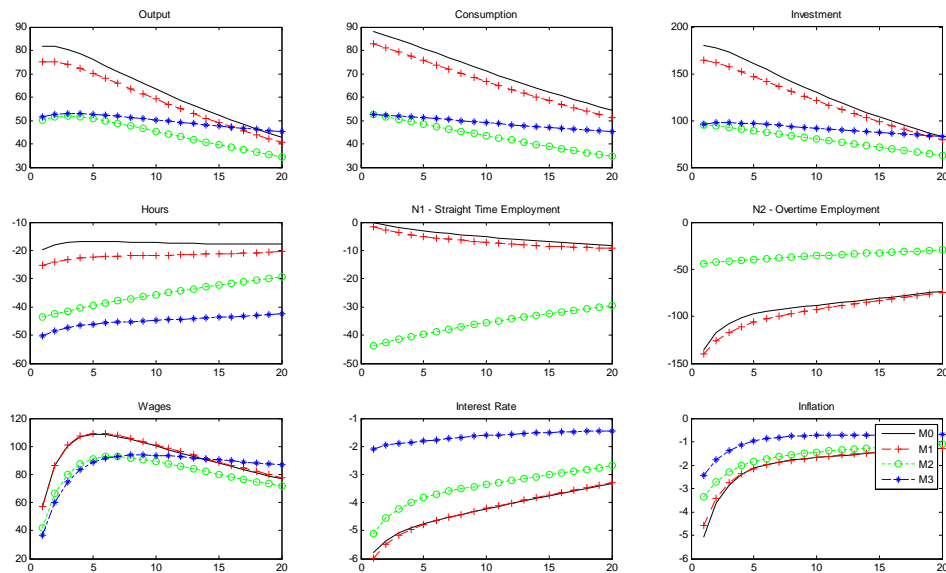


Figure 2: Risk Premium shock

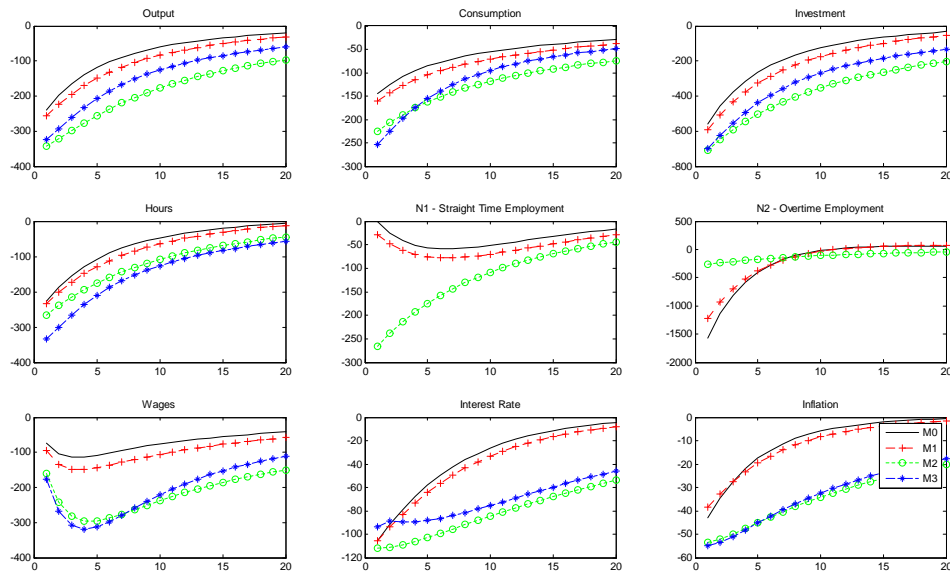


Figure 3: Fiscal shock

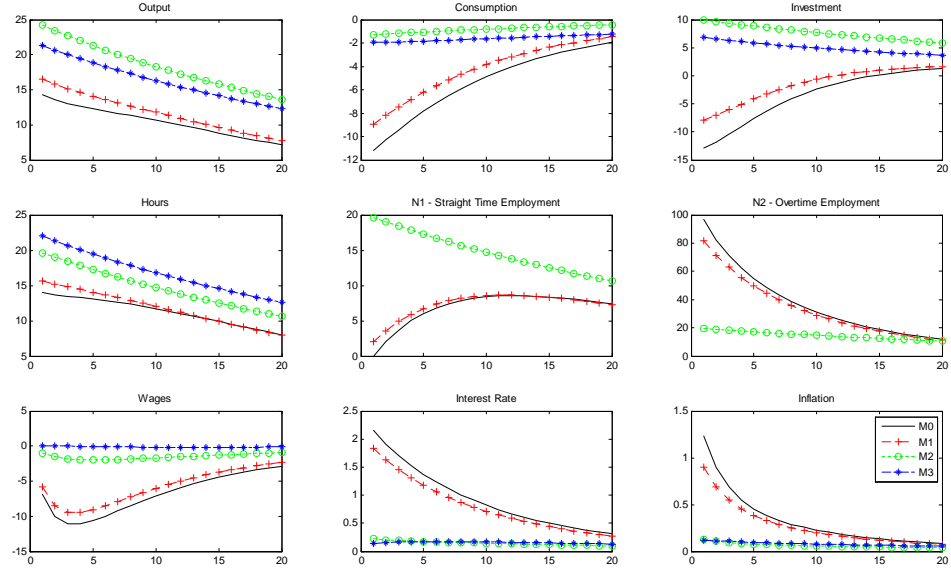


Figure 4: Monetary Policy shock

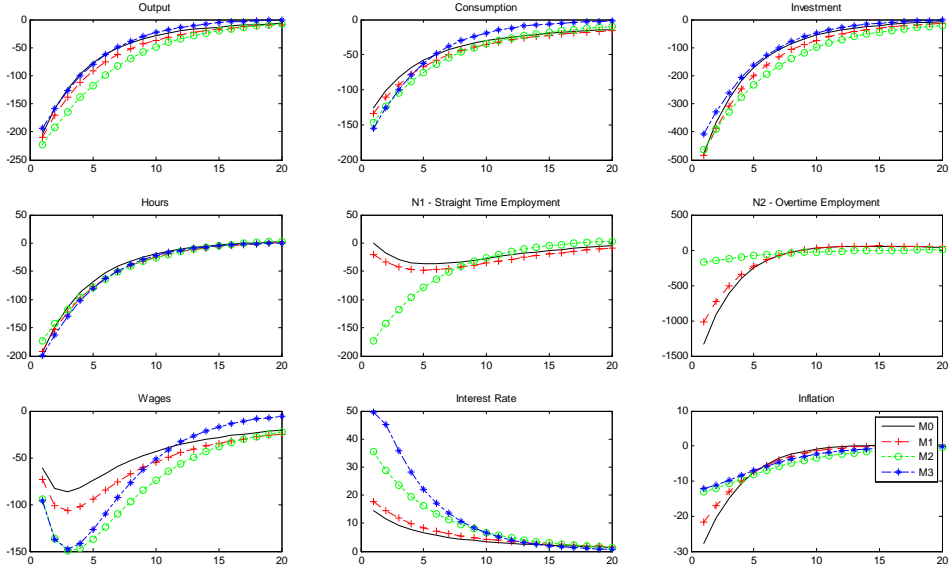


Figure 5: Investment-Specific Technology shock

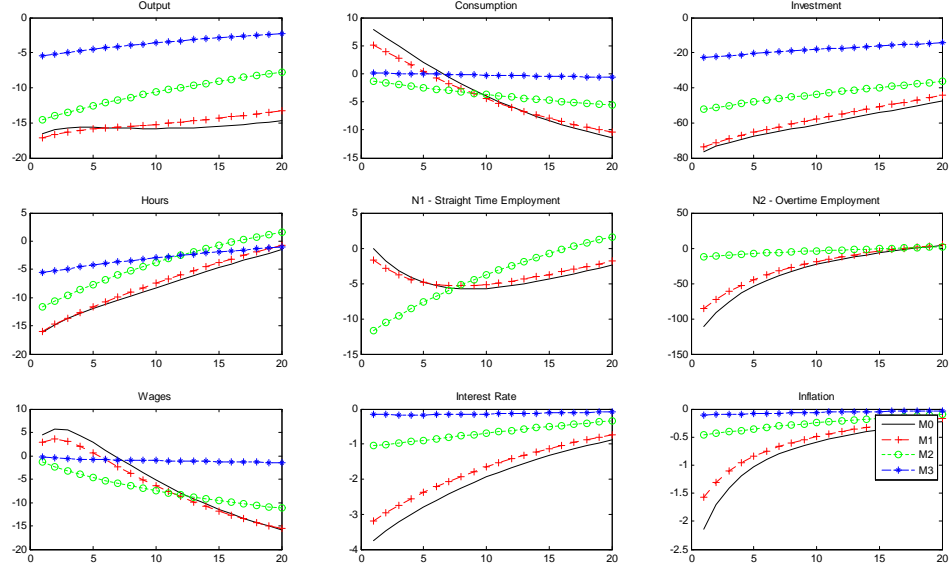


Figure 6: Price Mark-Up shock

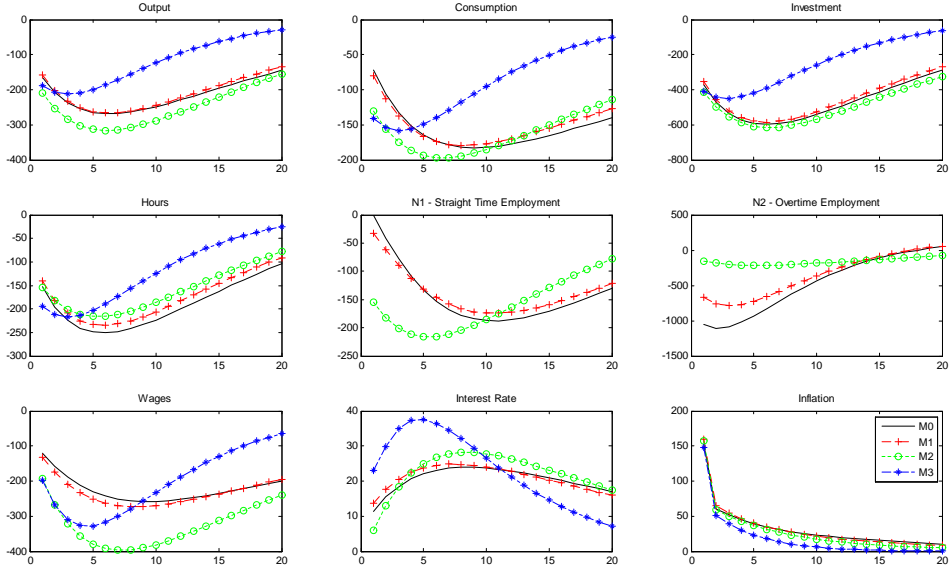
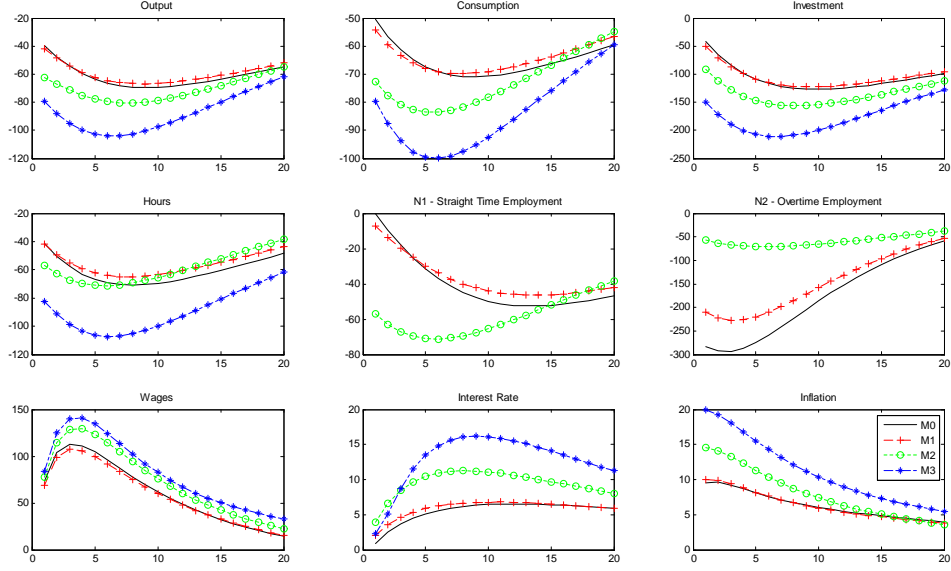


Figure 7: Labor Supply shock



8 Appendix

8.1 Steady State

$$MC = \frac{1}{1 + \lambda_P} \quad (\text{S1})$$

$$\tilde{\rho} = \frac{\Theta}{\beta\eta^{-\sigma}} - (\Theta - \delta_{N1}) \quad (\text{S2})$$

$$R^k = \frac{1}{\beta\eta^{-\sigma}} - (1 - \delta) = \Psi'(1) \quad (\text{S3})$$

Steady state values for \tilde{K} , \tilde{W}_1 , \tilde{W}_2 , N_1 , N_2 and \tilde{C} are obtained by solving the system of equations:

$$\tilde{K} = (\alpha N^* \frac{MC}{R^k})^{\frac{1}{1-\alpha}} \quad (\text{S4})$$

$$\frac{\tilde{W}_2}{1 + \lambda_w} = ((a_2 - a_1)\tilde{C}^\sigma)/h_2, \quad (\text{S5})$$

$$\frac{\tilde{W}_1}{1 + \lambda_w} = ((a_1 - a_0)\tilde{C}^\sigma)/h_1, \quad (\text{S6})$$

$$MC = \frac{\tilde{W}_2}{(1 - \alpha)\tilde{K}^\alpha N_2^{-\alpha}}, \quad (\text{S7})$$

$$\tilde{\rho} + \tilde{W}_1 h_1 = MC(1 - \alpha)\tilde{K}^\alpha h_1 N_1^{-\alpha} \quad (\text{S8})$$

$$\tilde{C} = \tilde{K}^\alpha N^* - \delta\tilde{K} - sg\tilde{K}^\alpha N^* - \delta_{N1}N_1. \quad (\text{S9})$$

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

One can then obtain:

$$\tilde{Y} = \tilde{K}^\alpha N^* \quad (\text{S10})$$

$$\tilde{G} = sg\tilde{Y} \quad (\text{S11})$$

$$\tilde{I} = \delta\tilde{K} \quad (\text{S12})$$

$$\tilde{H} = \delta_{N1}N_1, \quad (\text{S13})$$

In steady state $u = 1$ and it is assumed that the cost of capital utilization is zero when capital utilization is one $\Psi(1) = 0$.

8.2 Log-Linear Expansions

8.2.1 The Labor Frictions Model

Lower case letters and hats denote variables in log deviation from the steady state.

$$\tilde{c}_t = E_t \tilde{c}_{t+1} - \frac{1}{\sigma}(r_t - E_t \pi_{t+1} + \hat{\varepsilon}_t^b), \quad (\text{L1})$$

$$\omega_t = \beta\eta^{-\sigma}\omega_{t+1} + \frac{(1 - \theta_w)(1 - \beta\eta^{-\sigma}\theta_w)}{\theta_w}[\sigma\tilde{c}_t + \hat{\varepsilon}_t^l - (\tilde{w}_t - p_t)], \quad (\text{L2})$$

$$\frac{(1 - \Psi)}{\Psi}r_t^k = \hat{u}_t, \quad (\text{L3})$$

$$\delta\tilde{i}_t = \tilde{k}_{t+1} - (1 - \delta)\tilde{k}_t + \delta\hat{\varepsilon}_t^i, \quad (\text{L4})$$

$$\begin{aligned}\tilde{k}_{t+1} = & \frac{1}{1 + \beta\eta^{-\sigma}}\tilde{k}_t + \frac{\beta\eta^{-\sigma}}{1 + \beta\eta^{-\sigma}}E_t\tilde{k}_{t+2} + \frac{\beta\eta^{-\sigma}R^k}{(1 + \beta\eta^{-\sigma})\epsilon_\psi}E_tr_{t+1}^k \\ & - \frac{1}{(1 + \beta\eta^{-\sigma})\epsilon_\psi}(r_t - E_t\pi_{t+1} + \hat{\varepsilon}_t^b) - \frac{1}{(1 + \beta\eta^{-\sigma})\epsilon_\psi}\hat{\varepsilon}_t^i + \frac{(1 - \delta)\beta\eta^{-\sigma}}{(1 + \beta\eta^{-\sigma})\epsilon_\psi}\hat{\varepsilon}_{t+1}^i, \end{aligned} \quad (\text{L5})$$

$$\delta_{N1}\tilde{h}_t = \Theta n_{1,t+1} - (\Theta - \delta_{N1})n_{1,t}, \quad (\text{L6})$$

$$n_{1,t+1} = \frac{1}{1 + \beta\eta^{-\sigma}}n_{1,t} + \frac{\beta\eta^{-\sigma}}{1 + \beta\eta^{-\sigma}}E_t n_{1,t+2} + \frac{\beta\eta^{-\sigma}\tilde{\rho}}{(1 + \beta\eta^{-\sigma})\epsilon_{\psi N1}}E_t\hat{\rho}_{t+1} - \frac{\Theta}{(1 + \beta\eta^{-\sigma})\epsilon_{\psi N1}}E_t(r_t - E_t\pi_{t+1} + \hat{\varepsilon}_t^b), \quad (\text{L7})$$

$$\tilde{Y}\tilde{y}_t = \tilde{Y}a_t + \tilde{Y}\alpha(\hat{u}_t + \tilde{k}_t) + (1 - \alpha)\tilde{K}^\alpha h_1 N_1^{1-\alpha} n_{1,t} + (1 - \alpha)\tilde{K}^\alpha h_2 N_2^{1-\alpha} n_{2,t}, \quad (\text{L8})$$

$$(h_1 N_1 + h_2 N_2)n_t = (h_1 N_1)n_{1,t} + (h_2 N_2)n_{2,t}, \quad (\text{L9})$$

$$mc_t = \tilde{w}_t - p_t - a_t + \alpha n_{2,t} - \alpha(\hat{u}_t + \tilde{k}_t), \quad (\text{L10})$$

$$\tilde{\rho}\hat{\rho}_t + h_1\tilde{W}_1(\tilde{w}_t - p_t) = (\tilde{\rho} + h_1\tilde{W}_1)(mc_t + a_t + \alpha(\hat{u}_t + \tilde{k}_t) - \alpha n_{1,t}) \quad (\text{L11})$$

$$mc_t = r_t^k - y_t + (\hat{u}_t + \tilde{k}_t). \quad (\text{L12})$$

$$\tilde{Y}\tilde{y}_t = \tilde{C}\tilde{c}_t + \tilde{G}\tilde{g}_t + \tilde{I}\tilde{i}_t + R^k\tilde{K}\hat{u}_t + \tilde{H}\tilde{h}_t, \quad (\text{L13})$$

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)(\gamma_\pi \pi_t + \gamma_y \tilde{y}_t) + \gamma_{\Delta y}(\tilde{y}_t - \tilde{y}_{t-1}) + u_t^r, \quad (\text{L14})$$

$$\pi_t = \beta\eta^{-\sigma}E_t\pi_{t+1} + \frac{(1 - \theta)(1 - \theta\beta\eta^{-\sigma})}{\theta}(mc_t + \hat{\lambda}_{p,t}), \quad (\text{L15})$$

$$\hat{\lambda}_{p,t} = \rho_p \hat{\lambda}_{p,t-1} - \mu_p u_{t-1}^p + u_t^p, \quad (\text{L16})$$

$$\hat{\varepsilon}_t^b = \rho_b \hat{\varepsilon}_{t-1}^b + u_t^b, \quad (\text{L17})$$

$$\hat{\varepsilon}_t^l = \rho_l \hat{\varepsilon}_{t-1}^l + u_t^l, \quad (\text{L18})$$

$$\hat{\varepsilon}_t^i = \rho_i \hat{\varepsilon}_{t-1}^i + u_t^i, \quad (\text{L19})$$

$$a_t = \rho_a a_{t-1} + u_t^a, \quad (\text{L20})$$

$$\tilde{g}_t = \rho_g \tilde{g}_{t-1} + u_t^g, \quad (\text{L21})$$

where $\omega_t = (\tilde{w}_t - \tilde{w}_{t-1})$, $\tilde{w}_{1,t} = \tilde{w}_{2,t} = \tilde{w}_t$.

As in Smets and Wouters (2007), I normalize some of the exogenous shocks by dividing them by a constant term. The normalization consists of defining new exogenous variables, $\hat{\varepsilon}_t^{l*} = \frac{(1-\theta_w)(1-\theta_w\beta\eta^{-\sigma})}{\theta_w} \hat{\varepsilon}_t^l$ and $\hat{\lambda}_{p,t}^* = \gamma \hat{\lambda}_{p,t}$ and estimating the standard deviation of the innovations to $\hat{\varepsilon}_t^{l*}$ and $\hat{\lambda}_{p,t}^*$ instead of $\hat{\varepsilon}_t^l$ and $\hat{\lambda}_{p,t}$.

8.2.2 Comparison Model 1

Comparison model 1 is identical to the baseline model but $N_{1,t}$ is no longer assumed to be predetermined. Equations (L6) and (L7) are substituted by:

$$\delta_{N1} \tilde{h}_t = \Theta n_{1,t} - (\Theta - \delta_{N1}) n_{1,t-1}, \quad (\text{L22})$$

$$n_{1,t} = \frac{1}{1 + \beta\eta^{-\sigma}} n_{1,t-1} + \frac{\beta\eta^{-\sigma}}{1 + \beta\eta^{-\sigma}} E_t n_{1,t+1} + \frac{\tilde{\rho}}{(1 + \beta\eta^{-\sigma}) \epsilon_{\psi N1}} \hat{\rho}_t - \frac{\Theta + \tilde{\rho}}{(1 + \beta\eta^{-\sigma}) \epsilon_{\psi N1}} E_t (r_t - E_t \pi_{t+1} + \hat{\varepsilon}_t^b), \quad (\text{L23})$$

The log-linear model consists of equations (L1) to (L5) and (L8) to (L23). The steady state equation (S2) is replaced by:

$$\tilde{\rho} = \Theta - \beta\eta^{-\sigma}(\Theta - \delta_{N1}) \quad (\text{S14})$$

The model's steady state is now given by (S1), (S3) to (S13) and (S14).

8.2.3 Comparison Model 2

Comparison model 2 is identical to comparison model 1 but with no hiring and labor adjustment costs ($\delta_{N1} = \Theta = \epsilon_{\psi N1} = 0$).

8.2.4 Comparison Model 3

This model consists of a very conventional New Keynesian model where labor is neither indivisible labor or predetermined. In this model equations (L2), (L8), (L10) and (L13) are replaced by:

$$\omega_t = \beta\eta^{-\sigma}\omega_{t+1} + \frac{(1-\theta_w)(1-\beta\eta^{-\sigma}\theta_w)}{\theta_w}[\sigma\tilde{c}_t + \hat{\varepsilon}_t^l + \chi\frac{N}{1-N}n_t - (\tilde{w}_t - p_t)], \quad (\text{L24})$$

$$\tilde{y}_t = a_t + \alpha(\hat{u}_t + \tilde{k}_t) + (1-\alpha)n_t, \quad (\text{L25})$$

$$mc_t = \tilde{w}_t - p_t - a_t + \alpha n_t - \alpha(\hat{u}_t + \tilde{k}_t), \quad (\text{L26})$$

$$\tilde{Y}\tilde{y}_t = \tilde{C}\tilde{c}_t + \tilde{G}\tilde{g}_t + \tilde{I}\tilde{i}_t + R^k\tilde{K}\hat{u}_t \quad (\text{L27})$$

The log-linear model consists of equations (L1), (L3) to (L5), (L12), (L14) to (L21) and (L24) to (L27).

The steady state of this model is calculated from (S1), (S3) and then obtaining steady state values for \tilde{K}, \tilde{W}, N and \tilde{C} by solving the following system of equations:

$$\tilde{K} = (\alpha\frac{MC}{R^k})^{\frac{1}{1-\alpha}}N \quad (\text{S15})$$

$$\tilde{W} = MC(1-\alpha)\tilde{K}^\alpha N^{-\alpha} \quad (\text{S16})$$

$$\tilde{C}^{-\sigma}\frac{\tilde{W}}{1+\mu_w} = v(1-N)^{-\chi} \quad (\text{S17})$$

$$\tilde{C} = \tilde{K}^\alpha N^{1-\alpha} - \delta\tilde{K} - sg\tilde{K}^\alpha N^{1-\alpha}. \quad (\text{S18})$$

The remaining steady state values are obtained from (S11), (S12) while \tilde{Y} is given by:

$$\tilde{Y} = \tilde{K}^\alpha N^{1-\alpha}. \quad (\text{S19})$$