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JEL classification: E24, E32, E52, J64.

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What Can a New Keynesian Labor Matching Model Match?

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I Introduction

The Diamond-Mortensen-Pissarides search and matching model has become the workhorse model for macroeconomists who wish to discuss labor market dynamics. Augmented with nominal imperfections, quite often in the New Keynesian tradition, it has become the standard framework used to talk about decisions made in hiring, firing, and wages with respect to business cycles. Paralleling developments in the rest of the business cycle literature, attention has turned toward adding more realistic features such as sticky wages to these models in an attempt to match certain business cycle facts. Shimer (2005) and Hall (2005) argue that sticky real wages can amplifiy of shocks, since sticky wages will affect hiring decisions, while Krause and Lubik (2007) are more skeptical. Gertler and Trigari (2009), noting that stickiness is observed to be nominal, set up a model that features sticky nominal wages which emerge from staggered Nash bargaining. This paper seeks to investigate how the sticky wage model performs along a number of dimensions when confronted with real-world data, and in particular it looks at three things: The ability of the model to match the short-run volatility of the data conditional on shocks, the ability of the model to match the long-run comovements in the data (such as between inflation and unemployment), and the ability of the model to accurately describe hiring behavior. The sticky wage model does reasonably well at the first objective and it fails at the second and third objectives.

Much work has already gone into evaluating the empirical performance of search-and-matching models. Most notably, Gertler, Sala, and Trigari (2008) estimate their sticky-wage search and matching model using the methods of Smets and Wouters (2007). Their empirical model is a high-dimensional model with a large set of adjustment costs, a large array of shocks, and a high degree of wage indexation to inflation. This is an impressive achievement, but it comes with some costs. They manage to fit the data to the shocks because both objects have the same rank, but it is difficult to interpret some of these shocks. Yashiv (2006), Christoffel, Küster, and Linzert (2007), Beauchemin and Tasci (2008), Krause, Lopez-Salido, and Lubik (2008), Costain and Reiter (2008), Ríos-Rull and Santaeulàlia-Llopis (2008), Choi and Ríos-Rull (2008), Faccini and Ortigueira (2009), and Balleer (2009) have looked at more specific aspects of search and matching models (generally without sticky wages). These authors have criticized its ability to generate volatility in employment and in labor's share in response to productivity shocks and its difficulty in generating a positive vacancy-employment relationship when hiring and firing margins are both relevant. Many researchers have taken this to mean that the separation margin should be omitted from these models, though this paper will argue that the model actually does well on the separation margin.

This paper takes an approach between the typical moment-matching exercises and the large-scale estimation literature and asks which aspects of the data a medium-scale model can match using a standard array of shocks. The paper formulates a matching model in the New Keynesian tradition similar to that of Gertler and Trigari (2009) but with a separation margin and with a cost to holding money and then feeds through a series of shocks based on actual postwar US data. Based on the results, one can see how well the simulated data match observed variables such as job creation, job destruction, vacancies, labor's share, employment, and investment. One can also see which shocks appear to play a major role in business cycles and which ones do not. The structural shocks are shocks to neutral productivity, investment-specific productivity, long-run and short-run interest rates, and government spending, with out-of-model observation errors on inflation and employment playing a small role. Nothing forces the model to match the other observables, and seeing how things do not match up can offer guidance into where the search and matching model falls short as a business cycle model. The estimation is based on maximum likelihood and it takes the misspecification of the model as given.

Several results stand out. First of all, in the estimation procedure, the model favors a moderate degree of wage and price rigidity, and it can match the cyclical behavior but not the volatility of labor's share and job destruction. Sticky wages do appear to provide an important source of amplification. Secondly, the model appears to face a sharp tradeoff between matching short-run movements in the data and matching the negative long-run relationship between employment and inflation. The latter aspect of the data is best captured by a simple cost channel model like that of Walsh (2005) where money is used for transactions. The model also predicts too large of a long-run government spending multiplier. There is definitely a tension between matching the short-run and long-run aspects of the data if one wishes for the sticky wages which emerge from infrequent contracting to operate on the hiring margin.

As far as the estimated shock processes go, both neutral and investment-specific productivity shocks are an unimportant driver of business cycles. Capital prices may have generated a mild growth cycle as computing consistently became cheaper beginning in the early 1980s, and neutral productivity shocks are associated to a small degree with the onset of the 1973 and 1980 recessions. Government spending shocks and shocks to long-run inflation expectations are also relatively unimportant, with the exception of the Korean War. By far the most important structural shock is the autocorrelated Taylor rule shock, and that is the most difficult of the standard shocks to motivate. The entire array of shocks can only explain 16.5% of the short-run variance of employment, while increasing the amount of stickiness helps the model generate more volatility, closer to 43%. In no case does the model explain more than half of the volatility of employment using these standard shocks.

Looking at the hiring and separation margins, the model with endogenous separations has a difficult time matching the hiring margin (as is well known from the literature), though with very sticky wages and prices, there is some improvement. A specification with exogenous separations can generate more volatility because it has one more degree of freedom, but it predicts strongly countercyclical behavior in vacancies and hiring driven by the combination of free entry in vacancy postings and declining hiring costs driven by the matching function. Shutting down the separation margin generates hiring indicators which have better cyclical properties but worse volatility. This is the second major tension evident in trying to match these models to the data. One can match the hiring or separation margin but not both, and the data seem to indicate that it is the hiring margin of this standard model which fits the data worse.

II The data

This paper uses thirteen series which are put into a format compatible with the model (that is, demeaned or detrended in a statistically valid way). The first series is price inflation based on the NIPA PCE deflator. The second series is labor productivity in PCE terms, which is linearly detrended assuming a random walk with drift. The third series is the BEA's broad persons engaged series from the NIPA, which is interpolated using the BLS's CES nonfarm employment series. The series is taken to be 2% above trend in the first quarter of 1947, then at trend in the third quarter of 1955, the third quarter of 1963, the third quarter of 1970, the third quarter of 1978, the third quarter of 1987, the third quarter of 1996, and the third quarter of 2005. These dates were chosen because unemployment appeared to be roughly stable at its medium-run trend on these dates, and they accord well with the CBO's estimates of the employment gap. The fourth series is growth in M1, taken from the St. Louis Fed for the period after 1959 and Friedman and Schwartz (1963) for the period before 1959. The fifth series is the three-month treasury bill rate, and the sixth series is the NIPA corporate labor share.

The seventh series is the vacancy-employment ratio which is mostly based on the Conference Board's Help Wanted Index normalized by employment. Before 1957 the data come from the Met Life Help Wanted Index and are spliced to the latter series as explained by Zagorsky (1998). It is augmented by the Monster Online Help Wanted Index normalized by employment, which begins in 2003 and is projected back to the beginning of 1994 as done by Valletta (2005) by taking it to equal a linearly declining proportion of the print index. A consistent post-1994 HWI-based vacancy rate is then constructed by regressing post-2001 JOLTS vacancy rates on print and online HWI indices with no constant. The eighth and ninth series are the job destruction and creation rates published from the BED (now called the BDM on the BLS's website). They are extended back using the manufacturing-based data in Faberman (2006), by regressing the economywide totals on the composite manufacturing-based ones. These are used instead of the CPS-based measures used by others because they have a somewhat more consistent history going back to 1947, do not suffer from discontinuities, and they are well-documented. These series are not perfect but they still offer information about job flows from the establishment side which can be hard to get from other sources. The tenth series is the government consumption plus investment share of output, and the eleventh is the gross private investment share of output, both taken from the NIPA. The twelfth series is the linearly detrended real price of equipment, structures, and software. This is constructed as a Törnqvist index using the NIPA deflator for gross private investment ex equipment and software and the Cummins and Violante (2002) quality-adjusted deflator for equipment and software.[1]

The last series is the 10-to-20-year constant-maturity forward rate on treasury securities. This is intended as a measure of expected long-term interest rates (and inflation, based on the Fisher condition). There are two gaps in this series. The first gap is from 1987 to 1993, and this is interpolated by approximating the changes in the 10-to-20 year rate with changes in the 10-to-30-year rate and then correcting linearly for the error of closure. The other gap is the period before 1953. The NBER has series on 20-year treasury yields and 3-to-5-year treasury yields end in 1961. Luckily, this is a period of low and stable long-term interest rates. The post-1953 forward rate was regressed on these two yields in order to arrive at a predicted 10-to-20-year forward rate.

III The model

Walsh (2002, 2005), Trigari (2009), and Cooley and Quadrini (1999) present different models of job creation and destruction in the presence of nominal rigidities, building upon the search and matching model of Mortensen and Pissarides (1994) and den Haan, Ramey, and Watson (2000). Gertler and Trigari (2009) extend this approach

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[1] The author wishes to thank Gianluca Violante for graciously making these data available electronically. The data were interpolated to a quarterly frequency with the NIPA deflator.

to include sticky nominal wages, finding that this modification can better account for cyclical movements in output and wages. This model is based in large part on the latter model. This model has seven structural disturbances: Disturbances to government spending, neutral productivity, investment-specific productivity, long-run interest rates, short-run interest rates (and thus inflation), and short-run inflation. On the household side, there is a continuum of infinitely lived consumers. Production and hiring take place in a firm-worker match, with wages responding sluggishly to the bargaining environment. A retail sector aggregates output from the wholesale sector and resets retail prices in a staggered manner. The monetary authority follows a Taylor rule, augmented to account for nonstationary interest rates and for out-of-model shocks to inflation. Government spending and fixed investment, with variable utilization, round out the model.

III.A The household sector

Individuals within households supply labor inelastically; they either work for a set number of hours per week or do not work at all. They also have the choice between consuming in a given period and saving in nominal bonds to consume in the future. They each seek to maximize the objective function

$$E_t \sum_{i=0}^{\infty} \beta^i \left[\ln(C_{t+i} - hC_{t+i-1}) - \chi_{t+i} A_{t+i} \right], \tag{1}$$

where C_{t+i} equals the household's period-by-period real consumption and χ_{t+i} is an indicator variable equal to one if the household worked in a given period. For tractability, households are large and pool consumption efficiently.

Markets operate in three stages per period. In the first stage, after shocks are realized, financial markets open. People trade bonds and withdraw money in order to make their consumption purchases. In the second stage, the goods market opens and these purchases happen. In the third stage, income from the second stage is realized and factor payments are made. This delay introduces a cost channel into the model. This makes it possible for low nominal interest rates to directly stimulate production, since the opportunity cost of using money for transactions has fallen. This is an issue discussed by Walsh (2005) and, as the results below show, is consistent with some aspects of the data.

The traditional quantity equation, which is normally motivated by forcing people and firms to finance a portion of their spending with cash holdings, states that nominal consumption must not exceed end of period money holdings:

$$P_t Y_t \leq M_{t+1}. \tag{2}$$

In reality, the observed velocity of money is not constant, so (2) should have a term V_t on the right hand side in order to match it to the data, representing either shocks to the transactions technology or to the measurement of monetary aggregates. In a New Keynesian model such as this one, nominal spending is endogenously determined by interest rate policy, neutralizing any shocks to V_t. If one wishes to include money as an observable variable to track nominal output, it is necessary to have these shocks since money growth does not equal nominal output growth in reality.

The household's budget constraint is the usual one. B_t equals the household's purchases, at the beginning of the period, of one-period nominal bonds that mature at the beginning of the next period. They earn the gross nominal interest rate R_t. T_t equals the level of net taxes paid by the household, with a Ricardian fiscal policy:

$$M_{t+1} + B_{t+1} + P_t C_t + P_t I_t = P_t Y_t + R_{t-1} B_t + M_t - P_t T_t \,. \tag{3}$$

The household's first-order conditions also end up looking familiar. Optimization in bonds generates the usual intertemporal asset pricing relationship

$$\lambda_t = E_t \beta R_t \frac{P_t}{P_{t+1}} \lambda_{t+1} \,, \tag{4}$$

where the household's marginal utilities of consumption and wealth are equal:

$$\frac{1}{C_t - hC_{t-1}} - E_t \frac{\beta h}{C_{t+1} - hC_t} - \lambda_t = 0 \,. \tag{5}$$

Because of market clearing, output equals consumption plus investment and government spending, all in consumption units:

$$Y_t = C_t + G_t + I_t \,, \tag{6}$$

and the stochastic quantity equation holds:

$$P_t Y_t = V_t M_{t+1} \,. \tag{7}$$

III.B The retail sector and sticky prices

Monopolistically competitive retailers buy output competitively from the wholesale sector and resell it at a markup. They aggregate it according to a Dixit-Stiglitz aggregator. Retailers buy their products y_{jt} competitively from wholesale producers who produce homogeneous intermediate goods. The aggregate level of output is given by

$$Y_t = \left[\int_0^1 y_{jt}^{\frac{\theta-1}{\theta}} \, dj \right]^{\frac{\theta}{\theta-1}} , \tag{8}$$

for some substitutability parameter θ greater than one. From this expression, each individual retail firm faces a demand curve:

$$y_{jt} = \left(\frac{p_{jt}}{P_t}\right)^{-\theta} Y_t, \tag{9}$$

where the aggregate price level P_t equals the CES price index:

$$P_t = \left[\int_0^1 p_{jt}^{1-\theta} dj\right]^{\frac{1}{1-\theta}}. \tag{10}$$

The retailers buy unfinished output from the wholesalers at a price P_t^W and sell it at an aggregate markup $\mu_t \equiv P_t / P_t^W$. Each retailer, in the spirit of Calvo (1983), can only change its price with a probability 1 - ω.

Those firms that change their price in a given period do so symmetrically and reset their prices to p_t^*. They maximize expected discounted profits. Letting $D_{i,t+1}$ equal the discount factor $\beta^i(\lambda_{t+i}/\lambda_{t+1})$, the objective function for the price-changers equals

$$E_t \sum_{i=0}^{\infty} \omega^i D_{i,t+1} \left[\left(\frac{p_t^*}{P_{t+i}}\right)^{1-\theta} - \mu_{t+i}^{-1}\left(\frac{p_t^*}{P_{t+i}}\right)^{-\theta}\right] Y_{t+i}. \tag{11}$$

Long-run profit maximization results in the first order condition

$$\left(\frac{p_t^*}{P_t}\right) = \left(\frac{\theta}{\theta-1}\right) \frac{E_t \sum_{i=0}^{\infty} \omega^i D_{i,t+1} \mu_{t+i}^{-1} \left(\frac{P_{t+i}}{P_t}\right)^{\theta} Y_{t+i}}{E_t \sum_{i=0}^{\infty} \omega^i D_{i,t+1} \left(\frac{P_{t+i}}{P_t}\right)^{\theta-1} Y_{t+i}}, \tag{12}$$

with the aggregate retail price index given by

$$P_t^{1-\theta} = (1-\omega)(p_t^*)^{1-\theta} + \omega P_{t-1}^{1-\theta}. \tag{13}$$

Current prices are a weighted function of lagged prices and the prices set by those firms that could adjust. Conditions (12) and (13), when linearized and combined, describe a

New Keynesian Phillips Curve relationship which relates current retail markups to current and expected future inflation.

III.C The wholesale sector

The wholesale sector distinguishes this model from typical sticky-price or sticky-wage models. Workers and firms separate for both exogenous and endogenous reasons, and firms search for workers based on expectations of future profitability. Using standard notation, $U_t = 1 - N_t$ equals the number of workers searching for a job at the beginning of the period, with the population normalized to one. There is a constant probability ρ^x that a match will end exogenously. The remaining $(1 - \rho^x)N_t$ matches experience an iid, idiosyncratic productivity shock a_{it} (with a distribution function F) and a systematic permanent productivity shock z_t, all of which the worker and firm observe at the beginning of the period. Based on their realizations, the worker and firm decide whether to continue the relationship or to separate. If the relationship continues, the match produces $y_{it} = (a_{it} z_t)^{1-\alpha} k_{it}^{\alpha}$ which is sold at the wholesale price P_t^w to the retailers. If the relationship separates, production equals zero; the job is destroyed; and the worker becomes unemployed. All productivity shock processes have an unconditional mean of one and are iid over time. The idiosyncratic shocks are also independent and identically distributed over time and across agents.

Matches rent capital (priced in terms of consumption units) in a competitive rental market at a rate ρ_t^k, after all shocks are realized. Denoting the retailer's gross markup μ_t as P_t / P_t^w, the surplus of a match at period t equals the real value of the match's product in time t, minus the disutility of work in product terms,[2] plus the expected discounted continuation value of the match (denoted by q_{it}), minus the match's capital rental payments. Income payments are discounted by the nominal interest rate because of the cost channel induced by monetary frictions:

$$s_{it} = \frac{(a_{it} z_t)^{1-\alpha} (k_{it} / p_t^k)^{\alpha}}{\mu_t R_t} - \frac{A}{\lambda_t} + q_{it} - \frac{\rho_t^k k_{it}}{R_t}.$$

The value of k_{it} is determined optimally by the match, so that:

$$\frac{k_{it}}{p_t^k} = a_{it} z_t \left[\frac{\alpha}{\mu_t \rho_t^K p_t^k}\right]^{\frac{1}{1-\alpha}}. \tag{14}$$

Firms and workers bargain efficiently over the worker's marginal product:

$$s_{it} = \frac{(1-\alpha)(a_{it} z_t)^{1-\alpha} (k_{it} / p_t^k)^{\alpha}}{\mu_t R_t} - \frac{A}{\lambda_t} + q_{it},$$

so substituting in the firm's capital demand, one can find the reduced form of the surplus:

$$s_{it} = \frac{(1-\alpha)(a_{it} z_t)}{\mu_t R_t} \left[\frac{\alpha}{\mu_t \rho_t^K p_t^k}\right]^{\frac{\alpha}{1-\alpha}} - \frac{A}{\lambda_t} + q_{it}.$$

After consolidating terms some more, one obtains the expression:

$$s_{it} = \frac{(1-\alpha)(a_{it} z_t)}{\mu_t^{\frac{1}{1-\alpha}} R_t} \left[\frac{\alpha}{p_t^k \rho_t^K}\right]^{\frac{\alpha}{1-\alpha}} - \frac{A}{\lambda_t} + q_{it}. \tag{15}$$

For a match to have positive surplus and continue, it will require that a_{it} exceed a certain cutoff $\tilde{a}_t$. Since the shock a_{it} is iid, the continuation value q_{it} will equal the same value q_t across matches. Setting (14) to zero gives the value of this cutoff:

[2] Treating the outside option as leisure ensures balanced growth. Gertler, Sala, and Trigari (2008) simply make the outside option proportional to the capital stock.

$$\tilde{a}_t = \frac{\mu_t^{\frac{1}{1-\alpha}} R_t (A/\lambda_t - q_t)}{z_t(1-\alpha)} \left[\frac{\rho_t^K p_t^K}{\alpha} \right]^{\frac{\alpha}{1-\alpha}}. \tag{16}$$

If a_{it} has the distribution F, then the endogenous separation probability ρ_t^n equals $F(\tilde{a}_t)$ and the aggregate separation rate ρ_t and the match survival rate φ_t are given by:

$$\rho_t = \rho^x + (1-\rho^x)F(\tilde{a}_t), \tag{17}$$

and

$$\varphi_t = (1-\rho^x)[1-F(\tilde{a}_t)] = (1-\rho_t). \tag{18}$$

In most models of this sort, workers and firms bargain every period. This model instead exhibits wage stickiness. As in Gertler and Trigari (2009), wages are determined through staggered Nash bargaining. With probability 1 - υ, wages are bargained such that the worker receives a share η of the bilateral surplus, and the firm receives the remainder. Otherwise, the nominal wage does not change. Newly hired workers receive a wage drawn at random from the prevailing wage distribution and are otherwise like old workers. In this situation the wage does not directly affect the bilateral surplus or the separation rate between firms and workers. It may have important spillover effects as wages strongly affect vacancy posting, and this affects other aspects of the system.[3]

Firms can post vacancies at a fixed cost γp_t^v but face no other barriers to entry. These vacancies get filled at a gross rate k_t^f. A firm's portion of the surplus at any given date is denoted s_{it}^f. Equating the supply and demand for vacancies results in a condition equating the present value of a firm's vacancy posting with the cost of vacancy posting:

[3] One could alternately treat the equilibrium wage as holding for everyone out of fairness considerations, but responding sluggishly to the average Nash-bargained solution, or use a simple compensation smoother.

$$\gamma p_t^v = (1-\rho^x) k_t^f \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \int_{\bar{a}_{t+1}}^{\infty} s_{it+1}^f dF(a_{it+1}). \tag{19}$$

The probability of the worker actually finding a match equals k_t^w, based on a matching function. These conditions give the continuation value of the surplus:

$$q_t = (1-\rho^x)\beta E_t \frac{\lambda_{t+1}}{\lambda_t}(1-k_t^w)\int_{\bar{a}_{t+1}}^{\infty} s_{it+1} dF(a_{it+1}) + \frac{k_t^w \gamma p_t^v}{k_t^f}. \tag{20}$$

The cost of a vacancy has to grow with productivity in order to keep the vacancy-employment ratio stable over time. The exact way that this is done does not have a significant effect on the results, so posting costs are simply proportional to long-run productivity:

$$\gamma p_t^v = \gamma z_t (p_t^k)^{\frac{-\alpha}{1-\alpha}}. \tag{21}$$

The firm's portion of the surplus is given by:

$$s_{it}^f = \frac{(1-\alpha)(a_{it} z_t)^{1-\alpha}(k_{it} / p_t^k)^{\alpha}}{\mu_t R_t} - \frac{w_{it}}{R_t}$$

$$+ (1-\rho^x)\beta E_t \frac{\lambda_{t+1}}{\lambda_t} \int_{\bar{a}_{t+1}}^{\infty} s_{it+1}^f dF(a_{it+1}). \tag{22}$$

Aggregating things, the total number of unemployed in a period equals the starting stock of unemployed plus those who separate at the beginning of the period. Abstracting from labor force entry and exit, this comes out to

$$u_t \equiv U_t + \rho_t N_t = 1 - (1-\rho_t) N_t. \tag{23}$$

The number of vacancies posted in a given period equals v_t. Given a constant-returns Cobb-Douglas matching function $m(u_t, v_t) = \varsigma u_t^a v_t^{1-a}$, the vacancy-filling rate is given by

$$k_t^f = \frac{m(u_t, v_t)}{v_t}, \tag{24}$$

and the worker's job-finding rate is given by

$$k_t^w = \frac{m(u_t, v_t)}{u_t}. \tag{25}$$

The number of matches evolves according to the accounting identity

$$N_{t+1} = (1-\rho_t)N_t + m(u_t, v_t), \tag{26}$$

and the gross output of the matched firms and workers is given by

$$Q_t = \frac{(1-\rho_t)N_t z_t\left[\int_{\tilde{a}_t}^{\infty} a_{it}\,dF(a_{it})\right]}{1-F(\tilde{a}_t)}\left[\frac{\alpha}{\mu_t\rho_t^K p_t^k}\right]^{\frac{\alpha}{1-\alpha}}. \tag{26}$$

Output (in value-added terms) equals gross output minus vacancy posting costs:

$$Y_t = Q_t - \gamma p_t^v v_t. \tag{27}$$

To solve for the rebargained real wage, one could note that those firms which pay the rebargained wage W_t^* have an average surplus of $(1-\eta)s_t$ from Nash bargaining. Since wages sometimes deviate from this, firms' actual portion of the surplus may be higher or lower than this value. This difference, in the aggregate, is simply equal to the present value of the wage gap L_t after accounting for the cost channel:

$$L_t = s_t^f - (1-\eta)s_t = E_t\sum_{i=0}^{\infty}\frac{\beta^i\lambda_{t+i}\Phi_{t+i,t}}{\lambda_{t+i}}\left(\frac{W_{t+i}^* - W_{t+i}}{R_{t+i}}\right),$$

or in difference equation form:

$$L_t = \frac{W_t^* - W_t}{R_t} + E_t\frac{\beta\lambda_{t1}\varphi_{t+1}L_{t+1}}{\lambda_t}, \tag{28}$$

where the cumulative match survival probability is given for i > 0 by

$$\Phi_{t+i,t} = \prod_{j=1}^{t+i}\varphi_{t+j},$$

and is equal to one for i = 0. The average nominal wage rate is given by:

$$P_t W_t = \upsilon P_{t-1} W_{t-1} + (1-\upsilon) P_t W_t^* . \tag{29}$$

The price of capital in consumption units is given by p_t^k, which in equilibrium is equal to the inverse of the level of investment-specific productivity. Capital depreciates at a rate $\delta\left(N_{t+1}^K\right)$ which reflects a positive relationship between depreciation and utilization. Capital holdings follow a first-order condition which comes from the household's optimal choice of investment:

$$1 = \beta E_t \frac{p_{t+1}^k \lambda_{t+1}}{p_t^k \lambda_t}\left[1 + \frac{\rho_{t+1}^K N_{t+1}^K - \delta\left(N_{t+1}^K\right)}{R_{t+1}}\right]. \tag{30}$$

Finally, optimal utilization is given by:

$$\rho_t^K = \delta\phi\left(N_{t+1}^K\right)^{\phi-1}, \tag{31}$$

and the capital accumulation equation is given by:

$$\frac{K_{t+1}}{p_{t+1}^k} = \left(1-\delta\left(N_t^K\right)\right)\frac{K_t}{p_t^k} + \frac{I_t}{p_t^k}. \tag{32}$$

III.D Shocks to technology and preferences

Letting Γ^z equal the long-run growth rate of labor-specific productivity, it is convenient to assume that it follows a highly persistent AR(1) on top of a time trend:

$$\ln(\bar{z}_t) - \Gamma^z t = \rho_{\bar{z}}\left[\ln(\bar{z}_{t-1}) - \Gamma^z(t-1)\right] + \varepsilon_t^z . \tag{33}$$

The level of government spending, G_t, follows a stationary AR(1) which corrects slowly toward the prevailing level of output (thus ensuring balanced growth):

$$\ln(G_t) = (1-\rho_G)\ln\left(\frac{G}{Y}\right) + (1-\rho_G)\ln(Y_t) + \rho_G \ln(G_{t-1}) + \varepsilon_t^G . \tag{34}$$

The price of capital, in consumption units, also follows an AR(1):

$$\ln(p_t^k) - \Pi^K t = \rho_{PK}\left[\ln(p_{t-1}^k) - \Pi^K (t-1)\right] + \varepsilon_t^{PK}. \tag{35}$$

The observed velocity of money follows a random walk with drift:

$$\Delta \ln(V_t) = \Gamma^V + \varepsilon_t^V. \tag{36}$$

III.E The monetary authority

The monetary authority follows a Taylor rule based on observed data, with a very persistent target built into it. It has a long-run inflation (and interest rate) target which follows an AR(1) with a very high persistence coefficient:

$$\pi_t^* = (1-\rho_{\pi^*})\overline{\pi} + \rho_{\pi^*}\pi_t^* + \varepsilon_t^{\pi^*}. \tag{37}$$

In the data, one can think of this as capturing the longer-term changes in inflation expectations coming from the end of Bretton Woods and the fall in desired inflation throughout the 1980s and 1990s. Goodfriend (1993) discusses how rises in the long-term interest rate reflected shocks to longer-run inflation expectations during that time, and how these shocks could be interpreted as “inflation scares” during which expectations became unanchored. More generally, this moving target is intended to capture the nonstationarity present in the interest rate and inflation data, breaking interest rates out into short-run and long-run components. It allows one to meaningfully discuss changes in trend inflation and their effects over time, which a simple Taylor rule does not allow.

The Taylor rule itself follows the form:

$$r_t = r + \pi_t^* + \rho_\pi(\pi_t - \pi_t^* - \varepsilon_t^\pi) + \rho_Y(\ln(Y_t) - \ln(Y_{t-1}) - \ln(\Gamma)) + e_t^r \quad (38),$$

where

$$e_t^r = \rho_r e_{t-1}^r + \varepsilon_t^r. \quad (39).$$

This is based on the Taylor Rule as used by Bordo, Erceg, Levin, and Michaels (2007) in their discussion of the Volcker disinflation, with an extra white noise error term ε_t^{π}. The monetary authority responds to observed inflation and output and not to their theoretical deviations from an efficient equilibrium.[4] The rule contains output growth instead of levels in order to offer a clean interpretation of π_t^* as the long-run component of inflation and interest rates. The exogenous term e_t^r represents a Taylor rule error. In all likelihood it contains things that the Fed is responding to which do not show up directly in observed output growth or inflation (for instance, the deflation scare of 2002-03).[5] It is necessary to have all three errors in order to allow for the three series on inflation, short-term interest rates, and long-term interest rates to have full rank; a reduced rank system would trivially not be able to match the data. The way the model is designed, the inflation observation error term does not feed through directly into future policy expectations, so its real effect is quite minimal compared with those of the more persistent shock. One can view this almost like an observation error which is a residual obtained after fitting the other two more important monetary shocks. It is important to match these series in order to get the wage stickiness and Phillips curve parameters right.

III.F Observation shocks

The structural model is of reduced rank in comparison to the data; there are not enough shocks in the model (seven interesting shocks) to generate a set of observables of full rank (thirteen observables). Gertler, Sala, and Trigari (2008) solve this problem by

[4] See Cochrane (2007) for why it matters for identification purposes to have authorities respond to in-equilibrium rather than out-of-equilibrium values. Basically, out-of-equilibrium values are not observed.
[5] Orphanides (2003) discusses this error in the context of the extended information set of the Fed.

introducing extra shocks, for instance, to preferences and markups. In such a situation the model will trivially match the data, but it is hard to offer an economic interpretation to some of these shocks. This paper takes a different approach. This paper asks the question, given the well-motivated shocks and frictions that we typically include in our models, how well can we match certain aspects of the labor market? This estimation procedure is designed to see with which observables the model might be misspecified.

In this spirit, the model is forced to match the data on labor productivity, capital prices, government spending as a share of observed output, short and long term interest rates, and inflation. The additional variation in the data comes from autocorrelated observation errors on employment (equal to the error on output), labor's share of income, the vacancy-employment ratio, the job creation and destruction rates, and investment as a share of output. The interpretation of this exercise is, given what we observe about what appear to be reasonable driving processes, how does the model perform at matching other aspects of the data? Rather than viewing the model as a complete data generating process (as the likelihood-based estimation literature has done), this paper views the model as a mapping from assumptions to observables (as the early RBC theorists did) but with a likelihood-based evaluation procedure that goes well beyond matching a few moments.

III.G Equilibrium

The aggregate household conditions (4) through (7), the New Keynesian retail conditions (12) and (13), the aggregated versions of (14) through (32) from the wholesale sector, and the driving processes (33) through (39) constitute a rational expectations equilibrium for this economy. The method used to estimate the shocks hitting this economy involves taking a log-linear approximation around a steady state. Based on this linearized system, is possible to obtain feedback coefficients using the `gensys.m` program written and discussed by Sims (2002). In this particular situation, the equilibrium exists and is unique in the neighborhood around the steady state. One benefit of linearization is the ability to express the system as a moving average, thus being able to cleanly decompose movements in the economy into those caused by various shocks. Appendix A shows the detailed calculations of the steady state and linearized systems.

IV Estimation strategy

IV.A State space approach

The linearized model conveniently lends itself to a state space representation. Given a set of feedback rules and quarterly data on the variables of interest, it is fairly simple to use the Kalman Filter to estimate the underlying unobservable states. The filter also delivers the approximate Gaussian likelihood of the model. The first half of the state space approach consists of taking the underlying laws of motion of the model:

$$x_t = A_1 x_{t-1} + B_1 \varepsilon_t , \tag{39}$$

The second half of the state space approach consists of the observation equation relating the variables in the model to the eleven observed data series. One can label these series as x_t^*. Algebraically, this idea can be represented by the observation equation:

$$x_t^* = D_1 x_t . \tag{40}$$

The observation errors are included within the system as members of x_t, so it is not necessary to introduce other error terms into the system.

IV.B Calibrated and estimated parameter values

Most of the parameter values follow the calibrations used in Walsh (2002) or Gertler, Sala, and Trigari (2008), unless the data indicate another value. Households have a habit persistence coefficient h of 0.25, which maximizes the likelihood function; this is fairly low compared with some of the values used elsewhere. The results are not at all sensitive to this coefficient. The real interest rate equals 4.78 percent per year based on the average real interest rate in the data. Output per capita grows at a rate Γ of 1.87 percent per year, and real capital prices fall at 1.48 percent per year, implying a value of β of 0.995. Investment (including residential structures but excluding consumer durables) is 16.1% of output based on NIPA data; depreciation is calibrated to 2.5% per quarter; and government spending is 20.2% of output based on NIPA data. Steady state utilization is normalized to 1.

Based on Walsh's calibration, the gross retail markup μ equals 1.11, for a value of θ of 10. Based on the likelihood function, retailers change their prices on average once every quarter, for a value of ω of 0.25. This implies more flexibility than Bils and Klenow's (2004) estimate of about 0.5 and is much less than the values close to 0.7 which are often used. Wages last for six months, for a value of υ of 0.5, also less than the value used by Gertler and Trigari. Following Walsh and others, the exogenous job separation rate ρ^x equals 0.068 and the total job separation rate ρ equals 0.10 per quarter. These values imply a value of $\rho^n = F(\tilde{a})$ equal to 0.0343 per quarter. The idiosyncratic process a_{it} is lognormal with an arithmetic mean of 1 and an estimated dispersion parameter σ_a of 0.56, for a central location parameter μ_a of -0.1568. This delivers a value for $\tilde{a}$ of 0.3084 and a match surplus equal to 53% of quarterly post-interest output.

The likelihood of the model in the baseline setup favors vacancy posting costs equal to 1.3 percent of output; this is slightly higher than the value of one percent used by Hairault (2002) and Andolfatto (1996). Not much solid external evidence exists on this parameter. The unemployment share a of the matching function equals 0.4. Walsh cites Blanchard and Diamond (1989, 1991) who use postwar CPS data to derive an estimate of 0.4, and an exploratory regression using the establishment data indicates that a value between 0.35 and 0.45 fits the data best. The steady-state unemployment rate u (after separations) equals 0.06 which is just above the average postwar CPS unemployment rate. The worker-finding rate k^f equals 0.7 and the job-finding rate k^w equals 0.6, both from Walsh's calibration. These imply that there are 0.0514 vacancies v in the steady state. The baseline calibration implies values of 0.2908 for labor's bargaining power η and 0.9218 for the disutility of work A/λ. This equals 89% of the average post-interest wage, putting this model in a class of models with a moderately small surplus along with that of Hagedorn and Manovskii (2008).

The two long-run productivity processes and the long-run inflation process have coefficients of one, approximated as 0.9999 for numerical reasons. Based on the likelihood function, the Taylor rule has a coefficient of 1.5 on inflation (calibrated), 0.05 on output growth, and its error term has an autocorrelation of 0.93. Government spending has a persistence coefficient of 0.92. The observation error processes have a persistence of 0.995 for log employment and output, 0.96 for the log labor share, 0.97 for the log vacancy-employment ratio, 0.91 for the log job destruction rate, 0.98 for the log job creation rate, and 0.95 for the investment share of output.

There are four alternative calibrations which are also explored, where some parameter values are fixed and the rest of the model is reestimated holding vacancy posting costs above 1% of output and habit formation below 0.9. The first alternative, the flexible calibration, dispenses with sticky prices and wages and with monopolistic competition; the only channel of nominal transmission comes from the opportunity cost of holding money. The second one, the sticky calibration, sets both stickiness parameters to more conventional values (0.7 in both cases). The third calibration, the "constant-separation" calibration, involves taking the sticky model and setting the job destruction rate to be constant at 10% per quarter, and the fourth calibration, the "exogenous-separation" calibration, involves taking job destruction to follow an exogenous AR(1). This is done by replacing the job destruction condition (16) with an equation setting $\tilde{a}_t$ to 0, then in the latter case replacing the flow rate (18) with an AR(1). The latter two calibrations are discussed less than the first two, except as volatilities and cyclical properties are concerned; they exist in order to compare the results of the model with those of the Gertler and Trigari (who have constant separation rates).

V Estimation results

V.A Simulated vs. actual data

Figure 1 shows the estimated labor and capital market variables, along with their observable counterparts. The red 'x' lines show the observed data, while the solid blue lines show the filtered model-consistent data. It becomes immediately apparent that the model does not match the movements in the labor market variables at all given the conventional business cycle shocks. Given the estimated driving processes, the model predicts employment to be much smoother than it actually is. Apart from the Korean War boom and a small portion of the 1981-82 recession, the model generates nothing which looks like the recessions and booms actually observed in the employment data. The model does an even worse job at matching the movements in vacancies, labor's share, and hiring. It predicts that labor's share should not vary by much, because bargaining surpluses are rather small and wages are not especially inflexible. The model does not match vacancies or job creation at all; in the data they move sharply over the cycle, while in the model they wander around. The model does match job destruction somewhat better, though it is not nearly as countercyclical in the model as in the data.

Perhaps unsurprisingly, the model does not match investment dynamics either, though this appears to be an artifact of the more general difficulties of the model in producing business cycles. The model matches the behavior of short and long-term interest rates and inflation by construction. Of particular note, short-term inflation and interest rates are much more volatile than long-term interest rates, while long-term rates show relatively smooth behavior, with some volatility between the collapse of Bretton Woods and the late 1980s. Since that time, they have had a smooth downward trend. Government spending shows its familiar pattern, with a very large run-up during the Korean War and smaller increases, as a share of GDP, during the Vietnam and Reagan buildups. In the short run it is almost entirely dominated by military events.

V.B. Volatility and cyclicality

Table 1 shows the volatilities of the observables as predicted by the model under different calibrations, versus their volatilities as observed in the data. All variables are

HP-filtered with a smoothing parameter of 1600. The baseline model delivers too little volatility in every key aspect of the data, save the job creation rate. It does a better job than the flexible model but worse than the sticky model in this respect. None of these specifications produces a volatile labor share or enough volatility in the job destruction rate, though based on the ability to generate volatility alone, the sticky model appears to show the best results. This is the criterion given the most weight by Shimer (2005) and Hall (2005) in evaluating this class of models. The constant-separation generates low volatility except for the hiring-related variables, while the exogenous-separation model does well except for the fact that the hiring-related variables are too volatile. Based on a simple volatility-matching exercise, the best models are the sticky model and the exogenous-separation model, though the latter is more volatile almost by construction. As these two authors have emphasized, sticky wages can produce high volatility.

Table 2 shows the correlation of the model-generated variables with model-generated output as well as with their empirical counterparts, all using HP-filtered data. Model-generated employment is not as procyclical as it is in the data, while model-generated vacancies and job creation show the wrong cyclical properties altogether. The model matches the countercyclicality of the labor share reasonably well, and it has a difficult time generating a strong Phillips Curve relationship even with wage and price stickiness. On this front, most specifications show the wrong cyclical behavior of vacancies and hiring, with the exogenous-separation model showing the worst performance. The constant-separation model, on the other hand, completely misses the cyclical behavior of employment by shutting down an important channel of fluctuations which is at least consistent with the data.

Looking at Table 3, most variables are at least positively correlated with their empirical counterparts, except for vacancies. At high frequencies, the sticky model appears to work best at generating volatility and comovement, though even it still has difficulty in generating a Beveridge Curve. The sticky model is not any more correlated with the data than the baseline model, while the baseline model shows clear improvements over the flexible model in matching labor's share. Stickiness does seem to play an important role in matching the behavior of wages and employment. The exogenous-separation model again fares the worst, with job creation and vacancies showing strong negative correlations with their empirical counterparts.

V.C. The roles of the individual shocks

Figures 3 to 5 depict the effects of various shocks upon employment in the baseline model (the effects on output look very similar with the natural exception of productivity shocks). To construct these figures, the estimated shocks from 1947.III onward were fed into the model, and the resulting cumulative impulse responses charted. Figure 3 shows that monetary shocks do not appear to have played an important role in postwar business cycles, according to this model. According to the model, the burst of inflation caused by the unanchoring of expectations in 1973 should have provided substantial stimulus, while the data show a sharp recession beginning later that year. The same reasoning applies with the 1980 recession; expectations of higher long-run inflation should have fed through into higher vacancy creation. The model does predict a recession accompanying the disinflation of the early 1980s, but it predicts that this recession should be a correction of an abnormally stimulative policy. The short-run inflation control errors, by construction, show little effect since they are small one-time shocks and they do not feed through into policy or inflation expectations.

Figure 4 shows the effects of the estimated productivity shocks when fed through the model. The model predicts a small recession during what was really a small boom in the mid 1950s as equipment prices rose, while the model predicts a small boom during the onset of the computing revolution in the early 1980s. It does not appear that equipment prices account for the cyclical dynamics of any particular expansion or recession during the postwar period, though the computing revolution does appear to have stimulated investment somewhat. Based on neutral technology, the model predicts a small fall in employment during the 1973 and 1980 recessions, but nothing like the fall in employment actually observed during those episodes. Gertler, Sala, and Trigari (2008) come to an opposite conclusions regarding investment-specific technology shocks, though this may be because their study does not include such a shock in their list of observables, so they will tend to pin movements in investment on investment-specific productivity.

Figure 5 shows the role of government spending shocks along with the indirect effects of the observation shocks (which feed through into monetary policy decisions). Government spending produces a boom during the Korean War and provides a slight stimulus during the late 1960s and mid 1980s, just when one would expect military spending to have done so. In this model the government spending multiplier is roughly 0.59 (calculated as the cumulative increase in output divided by the cumulative increase in government spending in output units). Government spending crowds out both consumption and investment as resources get shifted from private into military use.

V.D. Accounting for variance and conditional volatility

Given the dynamic impulse responses and the moving-average nature of the linearized model, it is simple to do an in-sample variance decomposition for the endogenous variables. Table 4 shows the results of such a decomposition for employment; it describes what proportion of the observed variance in employment can be accounted for by each of these shocks acting in isolation. The first half of the table shows the results for HP-filtered data, while the second half shows the results for data which are unfiltered. For the filtered data, the model explains a very modest proportion of the variance of employment, 16.5% in the baseline scenario. Interest rate and government spending shocks provide the most variation in the data, with productivity shocks contributing amounts in the mid single digits. As one moves to the sticky model, interest rate shocks begin to look more important, and the short-run volatilities produced by the model begin to resemble those of the data a bit more.

Using unfiltered data, the individual shocks overexplain the variance of the data. This is because the simulated data inherit the very persistent components of inflation, government spending, and to some extent capital price changes. The model makes a strong prediction about the persistent components of employment based on sticky wages and prices, with high trend employment in particular during the late 1970s (because of inflation) and a downward trend from the early 1950s through the mid 2000s (because of declining government spending as a share of GDP). There seems to be a tradeoff between matching the long-run and short-run properties of the data, as this problem becomes worse as one adds stickiness to the model.

Table 5 takes the issue of variance decomposition one step further. It shows the results of regressing actual employment on the estimated impulse responses of the various shocks. It shows the same results for filtered and unfiltered data in some aspects. Using filtered data, the baseline specification has the best fit, with most coefficients near one and with the model explaining 61% of the variance of employment; this suggests that the baseline model does not suffer from a lack of amplification in general. The exceptions to this pattern are the effects of interest rate and inflation shocks, where the sticky model performs better. The sticky model completely gets the effects of long-run inflation shocks wrong. Using unfiltered data, in fact, the flexible calibration does best. The flexible model (whose only source of nominal nonneutrality is the cost channel of interest rate transmission) shows the correct long-run unemployment-inflation tradeoff. The unfiltered data are consistent with a cost channel but inconsistent with the idea that sticky nominal wages and prices play a large allocational role on the hiring margin.[6]

VI Conclusion

The results of the model evaluation exercise indicate that models which incorporate search and matching frictions in the RBC-New Keynesian Synthesis fail to match the data along several key dimensions, and introducing sticky wages and prices can come with its own tradeoffs. Based on the timing of productivity shocks, it is difficult to claim that neutral and investment-specific technological shocks are an important driver of the business cycle. Furthermore, based on the behavior of interest rates and inflation, it is difficult to claim that monetary shocks are an important driver of

[6] Gertler, Sala, and Trigari get around this by indexing quarterly wages to past inflation. Kahn (1997) shows that this does not happen in the micro data, and simulations suggest that indexation destroys much of the effect of nominal wage stickiness on the propagation of shocks.

the cycle, though there is some evidence that autocorrelated deviations from a Taylor Rule are important. Based on these shocks, the model fails to generate enough volatility in labor market outcomes, and it does a poor job at predicting the cyclical behavior of hiring indicators. Much of this is due to the fact that the shocks commonly discussed do not actually seem to drive most business cycles.

Adding further stickiness to wages and prices in order to increase volatility comes with a severe tradeoff. It allows the model to match the movements of macroeconomic aggregates better at high frequencies, at the expense of a total failure to match lower-frequency movements. The flexible-price model with a cost channel seems to do best at explaining the positive long-run relationship between inflation and unemployment, and adding indexation simply undoes most of the benefits of having stickiness in the model. There is also a tradeoff between matching movements on the job destruction margin and matching the job creation margin, though this is already a well-known result. Only by shutting off the job destruction margin can the model match the job creation margin. It is possible that both of these phenomena are related, since sticky wages operate on the job creation margin in this class of models. It is possible that it is the hiring margin, and not the separation margin, that needs to be rethought when taking this class of models to the data. The specification with endogenous separations does the best at matching the data, as Beauchemin and Tasci (2008) had hypothesized. This result confirms up their claim, using real-world data, that the problems with the model might lie on the hiring side.

Appendix A: Numerical solution to the model

A.1 Deriving the steady state from calibrated parameters

The state-space approach requires a specification for the state equation which comes from the linearized model. The linearized model in turn contains coefficients which depend on the steady state of the model. Deriving the steady state from the calibrated parameters is fairly straightforward. Given a nominal interest rate R, a balanced growth rate Γ, a gross inflation rate Π, and a risk aversion parameter σ, it is possible to calibrate the rate of time preference β after noting that the costate variable λ grows at rate Γ:

$$\beta = \frac{\Gamma\Pi}{\mathrm{R}}. \tag{A1}$$

In a zero-inflation steady state with a driftless velocity, the money growth rate $\overline{\Theta}$ simply equals the economic growth rate Γ. Given a markup μ, one can solve the equation

$$\mu = \frac{\theta}{\theta - 1},$$

to get θ.

Given a process for a_{it} and total and exogenous separation rates ρ and ρ^x, it is possible to derive the endogenous separation probability and the cutoff value for productivity:

$$\mathrm{F}(\tilde{\mathrm{a}}) = \rho^n = \frac{\rho - \rho^x}{(1 - \rho^x)}. \tag{A2}$$

Given an observed unemployment rate u as well as a total separation rate ρ, and job and worker finding rates k^w and k^f, it is easy to find the number of employed (before separations):

$$N = \frac{1-u}{1-\rho}, \tag{A3}$$

the number of vacancies from the homogeneous matching function,

$$k^f v = k^w u, \tag{A4}$$

and the retention rate:

$$\varphi = (1-\rho^x)[1-F(\tilde{a})]. \tag{A5}$$

The capital evolution equation and the rate of growth of capital prices, given a steady state investment ratio and depreciation rate, determines the steady-state capital-output ratio:

$$s_k = \frac{s_i \Pi^k}{(\Gamma - (1-\delta)\Pi^k)}, \tag{A6}$$

and the intertemporal investment equation determines ρ_k and the depreciation elasticity parameter:

$$\rho_k = \frac{R^2}{\Pi^k} - R + \delta, \tag{A7}$$

and

$$\phi_k = \frac{\rho_k}{\delta}. \tag{A8}$$

The demand for capital and the value of vacancy posting costs s_v determine the value of α:

$$\alpha = \frac{\rho_k s_k \mu}{1+s_v} \tag{A9}$$

Given the output equation, one can then find a value for gross output Q:

$$Q = \frac{(1-\rho)N\left[\int_{\tilde{a}_t}^{\infty} a_i dF(a_i)\right]}{1-F(\tilde{a})}\left[\frac{\alpha}{\mu\rho^K}\right]^{\frac{\alpha}{1-\alpha}}. \tag{A10}$$

This gives values for Y and γ based on the equation for value added:

$$Y = \frac{Q}{1+s_v}, \tag{A11}$$

and

$$\gamma p^v = \frac{Q-Y}{v}. \tag{A12}$$

The average surplus is taken from integrating over output in excess over the reservation value:

$$s = \frac{(1-\alpha)\left[\int_{\tilde{a}_t}^{\infty}(a_i-\tilde{a})dF(a_i)\right]}{(1-F(\tilde{a}))\mu R}\left[\frac{\alpha}{\mu\rho^K}\right]^{\frac{\alpha}{1-\alpha}}. \tag{A13}$$

The surplus equation a closed-form expression for q:

$$q = \frac{\varphi\Gamma(1-k^w)s}{R} + \frac{k^w\gamma p^v}{k^f}, \tag{A14}$$

and the vacancy posting condition yields the firm's share of the surplus:

$$s^f = \frac{\gamma R p^v}{k^f\varphi\Gamma}. \tag{A15}$$

The real wage follows the form (in steady state):

$$W = R\left(\frac{(1-\alpha)Q}{\varphi N\mu R} - s^f + \frac{\gamma p^v}{k^f}\right) \tag{A16}$$

and the rebargained wage is given by

$$W^* = W\frac{(1-\upsilon/\Gamma)}{(1-\upsilon)}. \tag{A17}$$

The initial value of the costate variable in consumption is determined by the first-order condition of the household's optimization problem:

$$\frac{1}{C - hC/\Gamma} - \frac{\beta h}{\Gamma C - hC} - \lambda = 0, \tag{A18}$$

and the surplus equation yields A:

$$A = \left(\frac{(1-\alpha)Q}{\varphi N \mu R} - s + q \right) \lambda . \tag{A19}$$

The price of vacancies can be normalized (by extension determining γ):

$$p^{v} = 1 . \tag{A20}$$

The initial value of the velocity does not matter for the calibration of this model and can be set to one.

A.2 Linearization around the steady state

Linearizing the quantity equation in first differences obtains the stochastic money demand relation (which determines observed velocity):

$$\hat{\pi}_t + \hat{y}_t + \hat{y}_t^{ERR} - \hat{\Theta}_t - \Delta \hat{V}_t = \hat{y}_{t-1} + \hat{y}_{t-1}^{ERR} . \tag{A21}$$

The evolution of the number of matches comes from the accounting condition after substituting the relationship between matches and vacancy filling:

$$\hat{n}_{t+1} = \varphi \hat{n}_t + \varphi \hat{\varphi}_t + \left(\frac{vk^f}{N} \right) \hat{v}_t + \left(\frac{vk^f}{N} \right) \hat{k}_t^f . \tag{A22}$$

The endogenous job destruction margin comes next:

$$\hat{a}_t = \hat{r}_t + \frac{1}{1-\alpha} \hat{\mu}_t + \frac{\alpha}{1-\alpha} \hat{\rho}_t^k + \frac{\alpha}{1-\alpha} \hat{p}_t^k - \hat{z}_t - \left(\frac{q}{A/\lambda - q} \right) \hat{q}_t$$

$$-\left(\frac{A/\lambda}{A/\lambda - q}\right)\hat{\lambda}_t, \tag{A23}$$

followed by an expression for the job retention rate:

$$\hat{\varphi}_t = -\left(\frac{\rho^n}{1-\rho^n}\right)e_{Fa}\hat{a}_t, \tag{A24}$$

where e_{Fa} equals the elasticity of F with respect to $\tilde{a}$. The number of job seekers is approximated by the expression

$$\hat{u}_t = -\left(\frac{\varphi N}{u}\right)\hat{\varphi}_t - \left(\frac{\varphi N}{u}\right)\hat{n}_t. \tag{A25}$$

The parameterization for the matching function ensures that the vacancy filling probability relates to vacancies and job searchers:

$$\hat{k}_t^f = a\hat{u}_t - a\hat{v}_t, \tag{A26}$$

and the job finding probability relates to the vacancy filling probability such that

$$\hat{k}_t^f + \hat{v}_t = \hat{k}_t^w + \hat{u}_t. \tag{A27}$$

Linearizing the job posting condition yields:

$$\hat{p}_t^v = \hat{k}_t^f - \hat{r}_t + E_t\hat{\pi}_{t+1} + E_t\hat{s}_{t+1}^f + E_t\hat{\phi}_{t+1}. \tag{A28}$$

Linearizing the output equation yields:

$$\hat{y}_t = \left(\frac{Q}{Y}\right)(e_{Ha}\hat{a}_t + \hat{\varphi}_t + \hat{n}_t + \hat{z}_t - \frac{\alpha}{1-\alpha}\hat{\mu}_t - \frac{\alpha}{1-\alpha}\hat{\rho}_t^k - \frac{\alpha}{1-\alpha}\hat{p}_t^k)$$

$$-\left(\frac{\gamma v p^v}{Y}\right)(\hat{v}_t + \hat{p}_t^v), \tag{A29}$$

where e_{Ha} equals the elasticity of $H(\tilde{a}) \equiv \frac{1}{1-F(\tilde{a})}\int_{\tilde{a}_t}^{\infty} a_i dF(a_i)$ with respect to $\tilde{a}$.

The asset pricing equation follows its typical form:

$$\hat{\lambda}_t = \hat{r}_t + E_t\hat{\lambda}_{t+1} - E_t\hat{\pi}_{t+1}, \tag{A30}$$

and the first-order condition for consumption becomes:

$$\frac{\Gamma^2 + \beta h^2}{(\Gamma - h)^2 C}\hat{c}_t - \frac{\Gamma\beta h}{(\Gamma - h)^2 C}E_t\hat{c}_{t+1} + \frac{\Gamma h}{(\Gamma - h)^2 C} - \lambda\hat{\lambda}_t = 0. \tag{A31}$$

The conditions for the retail sector give rise to a New Keynesian Phillips Curve linearized around a zero inflation steady state:

$$\frac{\omega}{R}E_t\hat{\pi}_{t+1} = \omega\hat{\pi}_t + (1-\omega)\left(1 - \frac{\omega}{R}\right)\hat{\mu}_t. \tag{A32}$$

The relationship between the continuation value of the surplus and future values of that surplus is approximated by the following:

$$\begin{aligned} q\hat{q}_t = {} & \frac{\varphi\bar{\Gamma}s(1-k^w)}{R}\left(E_t\hat{\varphi}_{t+1} - \hat{r}_t + E_t\hat{\pi}_{t+1} + E_t\hat{s}_{t+1}\right) \\ & + \left(\frac{k^w\gamma p^v}{k^f} - \frac{\varphi\bar{\Gamma}sk^w}{R}\right)\hat{k}_t^w + \frac{k^w\gamma p^v}{k^f}(\hat{p}_t^v - \hat{k}_t^f). \end{aligned} \tag{A33}$$

To get the factor shares and the continuation value of the match, it is helpful to have a linearized equation for the average surplus:

$$\begin{aligned} s\hat{s}_t = {} & \frac{(1-\alpha)Q}{\varphi N\mu R}\left(\frac{Y}{Q}\hat{y}_t + \frac{\gamma v p^v}{Q}\left(\hat{v}_t + \hat{p}_t^v\right) - \hat{\varphi}_t - \hat{n}_t - \hat{\mu}_t - \hat{r}_t\right) \\ & - \frac{A}{\lambda}\hat{\lambda}_t + q\hat{q}_t, \end{aligned} \tag{A34}$$

The surplus imbalance is linearized as follows (in levels, not log levels):

$$\hat{L}_t = s^f\hat{s}_t^f - (1-\eta)s\hat{s}_t, \tag{A35}$$

and the transition equation for this expected imbalance, which determines the wage bargain, is linearized as:

$$\hat{L}_t = \frac{W^*}{R}\hat{w}_t^* - \frac{W}{R}\hat{w}_t - \left(\frac{W^* - W}{R} + \frac{\varphi\Gamma L}{R}\right)\hat{r}_t + \frac{\varphi\Gamma L}{R}\left(E_t\hat{\varphi}_{t+1} + E_t\hat{\pi}_{t+1}\right)$$

$$+\frac{\varphi\Gamma}{R}E_t\hat{L}_{t+1}. \tag{A36}$$

The sticky wage equation becomes

$$W\hat{w}_t + (W - (1-\upsilon)W^*)\hat{\pi}_t - (1-\upsilon)W^*\hat{w}_t^* = \frac{\upsilon W}{\Gamma}\hat{w}_{t-1}. \tag{A37}$$

The firm's portion of the surplus, on average, is given as follows, after substituting in the job creation condition:

$$s_t^f = \frac{(1-\alpha)Q_t}{\varphi_t N_t \mu_t R_t} - \frac{W_t}{R_t} + \frac{\gamma p_t^v}{k_t^f},$$

so

$$s^f\hat{s}_t^f = \frac{(1-\alpha)Y}{\varphi N\mu R}\hat{y}_t + \frac{(1-\alpha)\gamma p^v v}{\varphi N\mu R}\hat{v}_t - \frac{(1-\alpha)Q}{\varphi N\mu R}\left(\hat{\mu}_t + \hat{\varphi}_t + \hat{n}_t\right)$$

$$-\frac{W}{R}\hat{w}_t + \left(\frac{\gamma p^v}{k^f} + \frac{(1-\alpha)\gamma v p^v}{\varphi N\mu R}\right)\hat{p}_t^v - \frac{\gamma p^v}{k^f}\hat{k}^f + \left(\frac{W}{R} - \frac{(1-\alpha)Q}{\varphi N\mu R}\right)\hat{r}_t. \tag{A38}$$

The resource constraint is linearized as

$$\hat{y}_t = s_c\hat{c}_t + s_i\hat{i}_t + s_g\hat{g}_t, \tag{A39}$$

and the capital transition equation, measured in consumption units, is linearized as

$$s_k\Gamma\hat{k}_{t+1} = s_k(1-s_\delta)\Pi^k\hat{k}_t + (s_k(1-s_\delta)+s_i)\Pi^k(\hat{p}_{t+1}^k - \hat{p}_t^k)$$

$$-\Pi^k s_\delta s_k\phi\hat{n}_t^k + s_i\Pi^k\hat{i}_t. \tag{A40}$$

The return to capital is given by

$$\hat{\rho}_t^k = \frac{Q}{Y}\hat{y}_t + \frac{\gamma p^v v}{Y}(\hat{v}_t + \hat{p}_t^v) - \hat{k}_t - \hat{n}_t^k - \hat{\mu}_t, \tag{A41}$$

and the investment equation is given by

$$\frac{R}{\Pi^k}(\hat{r}_t - E_t\hat{\pi}_{t+1} + \hat{p}_t^k - E_t\hat{p}_{t+1}^k) = \frac{\rho^k}{R}E_t\hat{\rho}_{t+1}^k + \left(\frac{\rho^k - s_\delta\phi}{R}\right)E_t\hat{n}_{t+1}^k$$

$$-\frac{\rho^k - s_\delta}{R}E_t\hat{r}_{t+1}, \tag{A42}$$

while the utilization equation is given by

$$\hat{\rho}_t^k = (\phi - 1)\hat{n}_t^k, \tag{A43}$$

and the price of a vacancy in output units is given by

$$\hat{p}_t^v = \hat{z}_t - \frac{\alpha}{1-\alpha}\hat{p}_t^k. \tag{A44}$$

Finally, it is necessary to include the seven structural shock processes:

$$\Delta\hat{V}_t = \varepsilon_t^V, \tag{A45}$$

$$\hat{g}_t = \rho_g\hat{g}_{t-1} + (1-\rho_g)(\hat{y}_t + \hat{y}_t^{ERR}) + \varepsilon_t^g, \tag{A46}$$

$$\hat{z}_t = \rho_{\bar{z}}\hat{z}_{t-1} + \varepsilon_t^z, \tag{A47}$$

$$\hat{r}_t = \hat{\pi}_t^* + \rho_\pi(\hat{\pi}_t - \hat{\pi}_t^* - \varepsilon_t^\pi) + \rho_Y(\hat{y}_t + \hat{y}_t^{ERR} - \hat{y}_{t-1} - \hat{y}_{t-1}^{ERR}) + e_t^r, \tag{A48}$$

$$e_t^r = \rho_r e_{t-1}^r + \varepsilon_t^r \tag{A49}$$

$$\hat{\pi}_t^* = \rho_{\pi^*}\hat{\pi}_{t-1}^* + \varepsilon_t^{\pi^*}, \tag{A50}$$

$$\hat{p}_t^k = \rho_{p^k}\hat{p}_t^k + \varepsilon_t^{p^k}, \tag{A51}$$

and the six observation error processes:

$$\hat{y}_t^{ERR} = \rho_y^{ERR}\hat{y}_{t-1}^{ERR} + \varepsilon_{y,t}^{ERR}, \tag{A52}$$

$$ls_t^{ERR} = \rho_{ls}^{ERR}ls_{t-1}^{ERR} + \varepsilon_{ls,t}^{ERR}, \tag{A53}$$

$$ve_t^{ERR} = \rho_{ve}^{ERR}ve_{t-1}^{ERR} + \varepsilon_{ve,t}^{ERR}, \tag{A54}$$

$$\mathrm{jd}_t^{ERR} = \rho_{jd}^{ERR}\,\mathrm{jd}_{t-1}^{ERR} + \varepsilon_{jd,t}^{ERR}, \tag{A55}$$

$$\mathrm{jc}_t^{ERR} = \rho_{jc}^{ERR}\,\mathrm{jc}_{t-1}^{ERR} + \varepsilon_{jc,t}^{ERR}, \tag{A56}$$

and

$$\mathrm{iy}_t^{ERR} = \rho_{iy}^{ERR}\mathrm{iy}_{t-1}^{ERR} + \varepsilon_{iy,t}^{ERR}. \tag{A57}$$

The end result of all of this is a VAR representation that provides the laws of motion for the underlying system for the state-observer setup. The observed variables from the data are taken as the model-consistent values plus their observation errors, all expressed in log deviations:

$$\hat{\pi}_t^{OBS} = \hat{\pi}_t, \tag{A58}$$

$$\mathrm{prod}_t^{OBS} = \hat{y}_t - \hat{n}_t - \hat{\varphi}_t, \tag{A59}$$

$$\mathrm{emp}_t^{OBS} = \hat{y}_t^{ERR} + \hat{n}_t + \hat{\varphi}_t, \tag{A60}$$

$$\hat{\Theta}_t^{OBS} = \hat{\Theta}_t, \tag{A61}$$

$$\hat{r}_t^{OBS} = \hat{r}_t. \tag{A62}$$

$$\mathrm{ls}_t^{OBS} = \mathrm{ls}_t^{ERR} + \hat{W}_t + \hat{n}_t + \hat{\varphi}_t - \hat{y}_t, \tag{A63}$$

$$\mathrm{ve}_t^{OBS} = \mathrm{ve}_t^{ERR} + \hat{v}_t - \hat{n}_t - \hat{\varphi}_t, \tag{A64}$$

$$\mathrm{jd}_t^{OBS} = \mathrm{jd}_t^{ERR} - \frac{\varphi}{1-\varphi}\hat{\varphi}_t, \tag{A65}$$

$$\mathrm{jc}_t^{OBS} = \mathrm{jc}_t^{ERR} + \hat{v}_t + \hat{k}_t^{f} - \hat{n}_t, \tag{A66}$$

$$\mathrm{gy}_t^{OBS} = \hat{g}_t - \hat{y}_t - \hat{y}_t^{ERR}, \tag{A67}$$

$$\mathrm{iy}_t^{OBS} = \mathrm{iy}_t^{ERR} + \hat{i}_t - \hat{y}_t - \hat{y}_t^{ERR}, \tag{A68}$$

$$p_t^{k,OBS} = \hat{p}_t^{k}, \tag{A69}$$

and

$$\hat{\pi}_t^{*,OBS} = \hat{\pi}_t^{*}. \tag{A70}$$

The latter set of equations forms the observation block of the system, from which the model-consistent variables are recovered using the Kalman Filter.

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Table 1 –Standard deviations of variables, data vs. model

Variable	Data	Flex	Baseline	Sticky	Const Sep	Exog Sep
Output	0.0171	0.0122	0.0120	0.0121	0.0100	0.0197
Employment	0.0139	0.0034	0.0057	0.0091	0.0045	0.0120
Vacancies	0.1450	0.0417	0.0637	0.1182	0.1147	0.1963
JD Rate	0.0802	0.0187	0.0286	0.0407	0	0.0802
JC Rate	0.0480	0.0459	0.0625	0.0965	0.0639	0.1700
Labor Share	0.0119	0.0002	0.0040	0.0068	0.0063	0.0065
Investment Share	0.0677	0.0347	0.0384	0.0656	0.0608	0.0534

Data are HP-filtered with a smoothing parameter of 1600. Source: See text.

Table 2 – Contemporaneous correlation of variables with output

Variable	Data	Flex	Baseline	Sticky	Const Sep	Exog Sep
Employment	0.76	0.45	0.39	0.49	-0.03	0.87
Vacancies	0.88	-0.46	-0.27	0.11	0.17	-0.66
JD Rate	-0.66	-0.46	-0.60	-0.53		-0.87
JC Rate	0.21	-0.45	-0.36	-0.21	0.19	-0.81
Labor Share	-0.34	-0.44	-0.40	-0.44	-0.59	-0.25
Inflation Rate	0.26	-0.22	-0.06	0.07	-0.16	0.12
Interest Rate	0.33	-0.30	0.06	0.39	0.06	0.14
Investment Share	0.76	0.66	0.65	0.76	0.73	0.84

Data are HP-filtered with a smoothing parameter of 1600 and then contemporaneous correlation coefficients are calculated. Source: See text.

Table 3 – Contemporaneous correlation of variables with own data (and likelihood)

Variable	Flex	Baseline	Sticky	Const Sep	Exog Sep
Output	0.60	0.77	0.78	0.62	0.80
Employment	0.18	0.66	0.64	0.28	0.59
Vacancies	-0.28	-0.14	-0.12	0.39	-0.44
JD Rate	0.15	0.42	0.33		1.00
JC Rate	0.14	0.21	0.24	0.21	-0.40
Labor Share	-0.04	0.41	0.48	0.47	0.41
Investment Share	0.37	0.40	0.44	0.40	0.53
Log Likelihood	**12,019.94**	**12,088.35**	**11,764.50**	**11,829.43**	**11,557.89**

Data are HP-filtered with a smoothing parameter of 1600 and then contemporaneous correlation coefficients are calculated. Source: See text.

Table 4 – In-sample variance decomposition for employment (filtered)

	Filtered			Unfiltered		
Shock	**Flex**	**Baseline**	**Sticky**	**Flex**	**Baseline**	**Sticky**
Government Spending	3.2%	8.4%	17.2%	31.1%	68.6%	151.4%
Neutral productivity	0.5%	6.0%	16.2%	1.4%	12.1%	21.2%
Capital prices	1.3%	6.5%	15.4%	9.5%	45.5%	79.3%
Long run inflation	0.2%	3.6%	10.7%	1.2%	41.7%	158.2%
Short run inflation	0.0%	0.9%	5.2%	0.0%	0.8%	2.3%
Interest rates	0.7%	9.7%	60.0%	0.7%	8.9%	61.2%
Employment observation error	0.7%	1.1%	2.1%	1.1%	5.0%	18.9%
Entire model	**6.1%**	**16.5%**	**42.9%**	**34.7%**	**55.4%**	**193.7%**

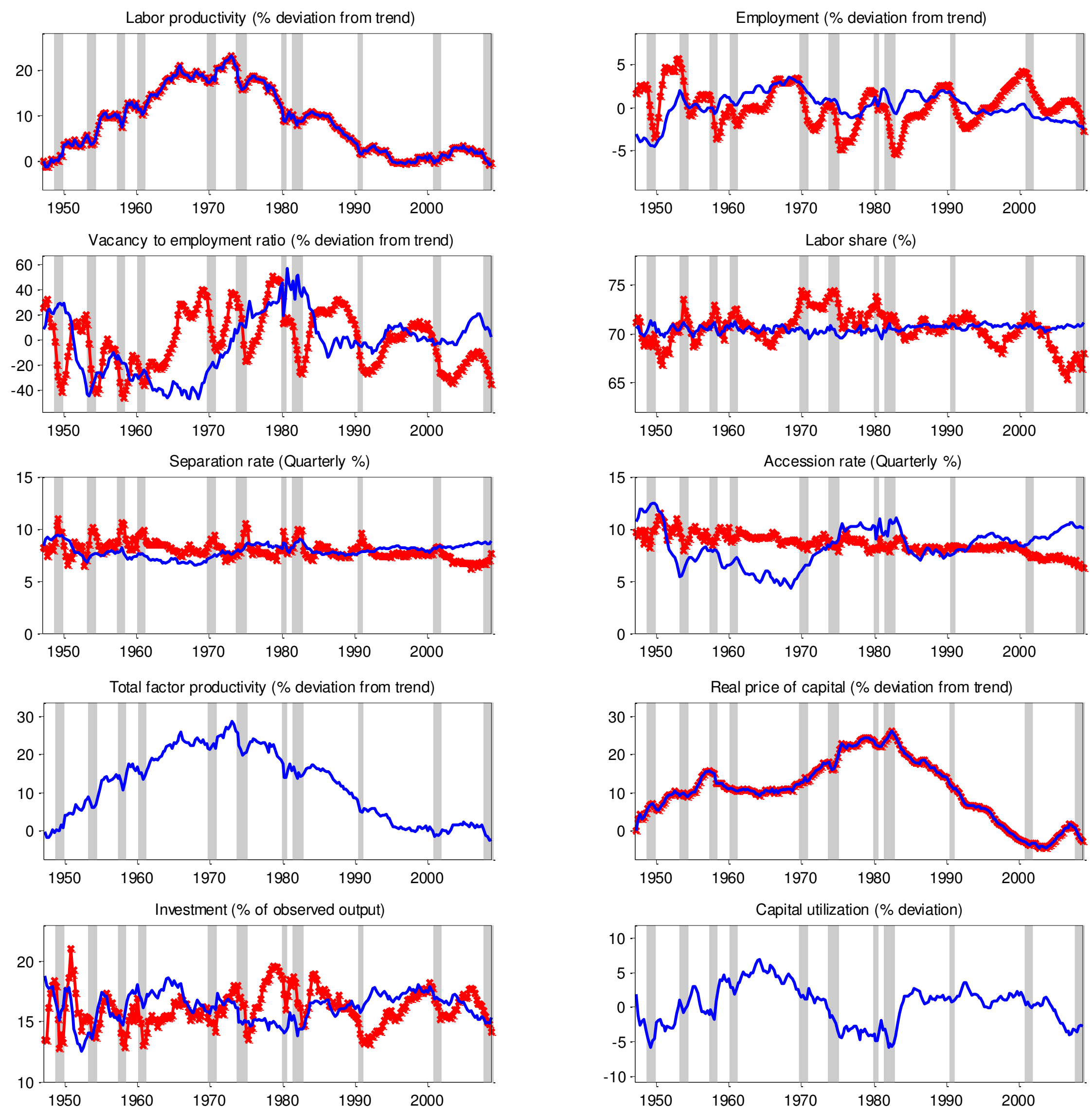
Filtered data are HP-filtered with a smoothing parameter of 1600. This table gives the contribution to the variance of employment of each shock, as a share of the overall variance in the data. Source: See text.

Table 5 – Regressions of observed employment on shock-based responses

	Filtered			Unfiltered		
Shock	**Flex**	**Baseline**	**Sticky**	**Flex**	**Baseline**	**Sticky**
Constant	0.000	0.000	0.000	0.000	0.014	0.013
(Standard Error)	0.001	0.001	0.001	0.003	0.004	0.002
Government Spending	1.868	1.487	0.753	0.552	0.193	0.266
(Standard Error)	0.275	0.148	0.130	0.118	0.076	0.064
Neutral productivity	3.891	1.509	0.306	2.017	0.674	0.806
(Standard Error)	0.848	0.197	0.162	0.752	0.259	0.189
Capital prices	2.019	0.823	0.778	2.812	1.172	0.788
(Standard Error)	0.466	0.176	0.144	0.240	0.116	0.071
Long run inflation	-1.670	0.897	-0.264	0.901	-0.395	-0.312
(Standard Error)	1.122	0.227	0.152	0.634	0.120	0.041
Short run inflation		6.463	0.640		3.391	0.908
(Standard Error)		0.504	0.271		0.707	0.360
Interest rates	-9.154	3.271	1.006	-9.048	2.454	1.038
(Standard Error)	0.682	0.176	0.085	0.672	0.230	0.087
R-Squared	**0.453**	**0.615**	**0.429**	**0.546**	**0.457**	**0.498**

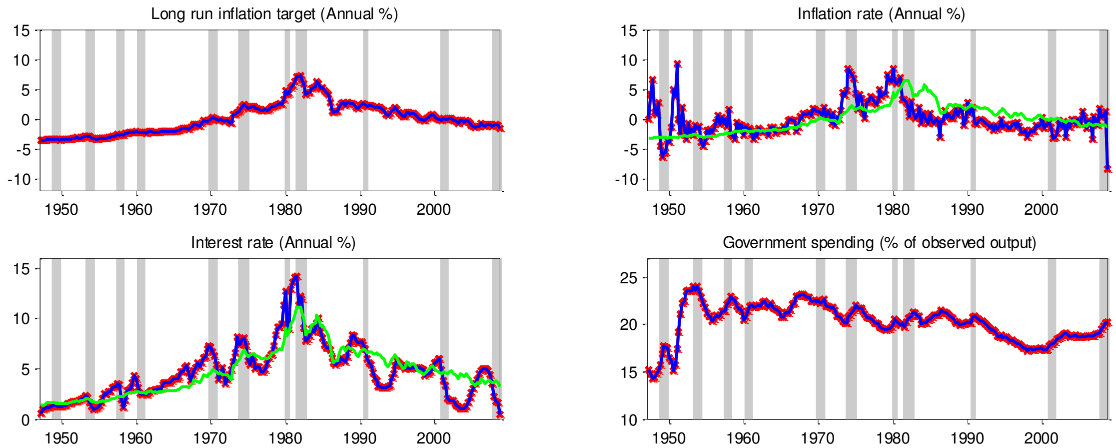
Filtered data are HP-filtered with a smoothing parameter of 1600. This table gives the results of regressing observed employment on predicted employment from each shock. Source: See text.

Figure 1 – Labor and capital market variables (observed vs model-generated)



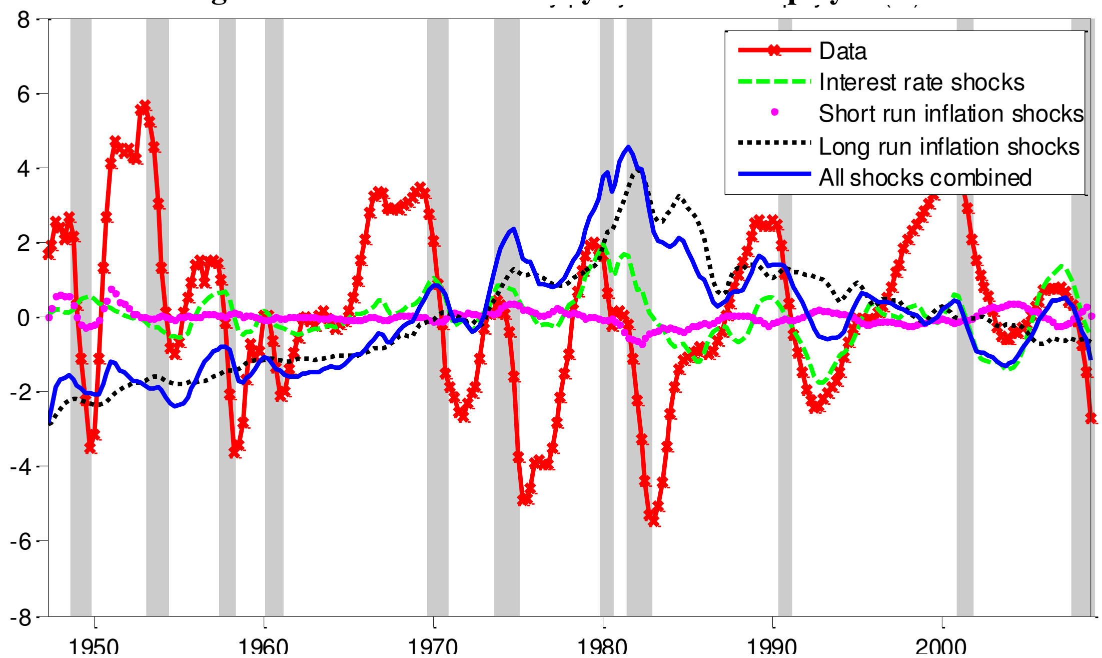
Red 'x' lines denote observed data; blue solid lines denote model-generated data as described in the text. For details on data sources and calculations, see text.

Figure 2 – Monetary and demand variables (observed vs model-generated)



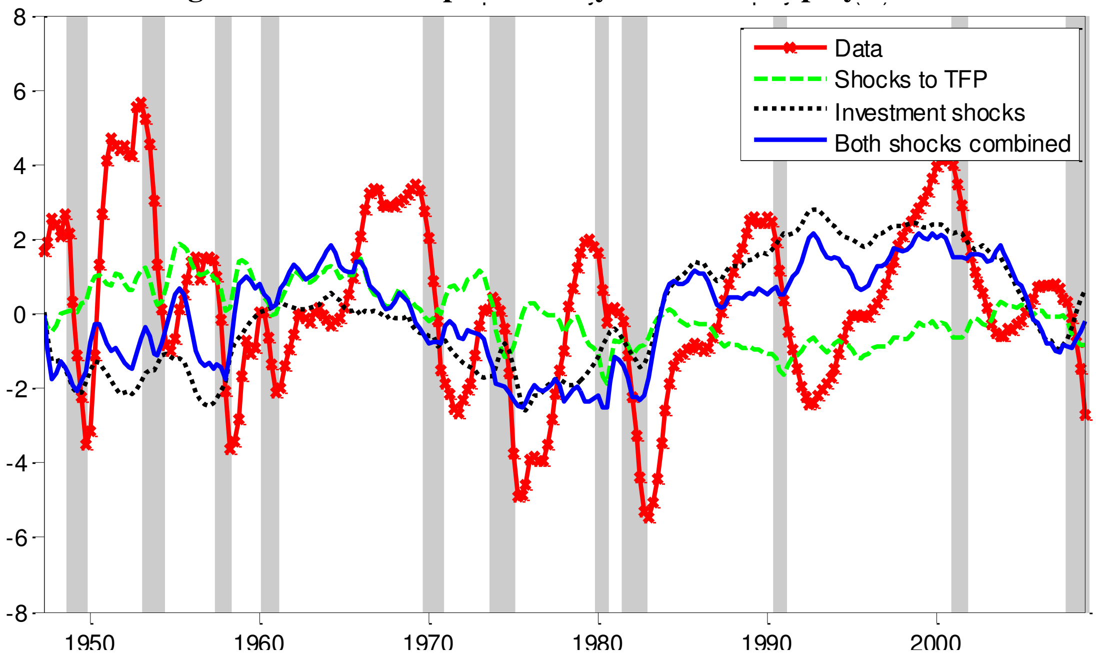
Red 'x' lines denote observed data; blue solid lines denote model-generated data as described in the text; and the light green line denotes trend inflation as given by long-term interest rates. For details on data sources and calculations, see text.

Figure 3 – Effects of monetary shocks on employment.



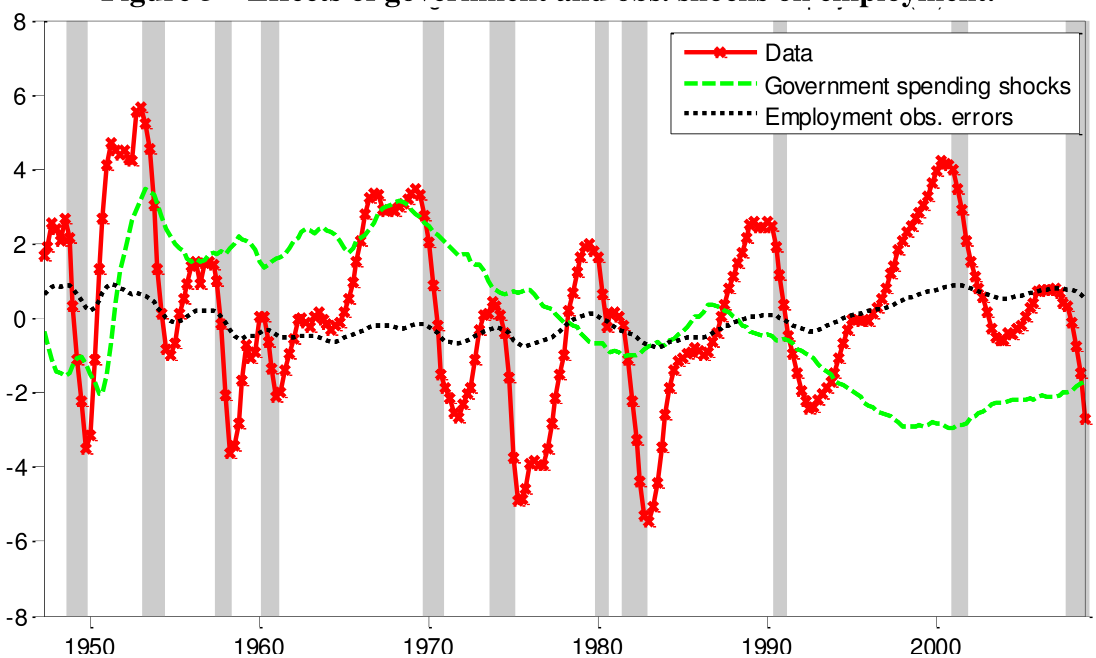
This figure shows the effects of the estimated shocks from 1947.III onward, when fed through the model. Gray lines indicate recessions.

Figure 4 – Effects of productivity shocks on employment.



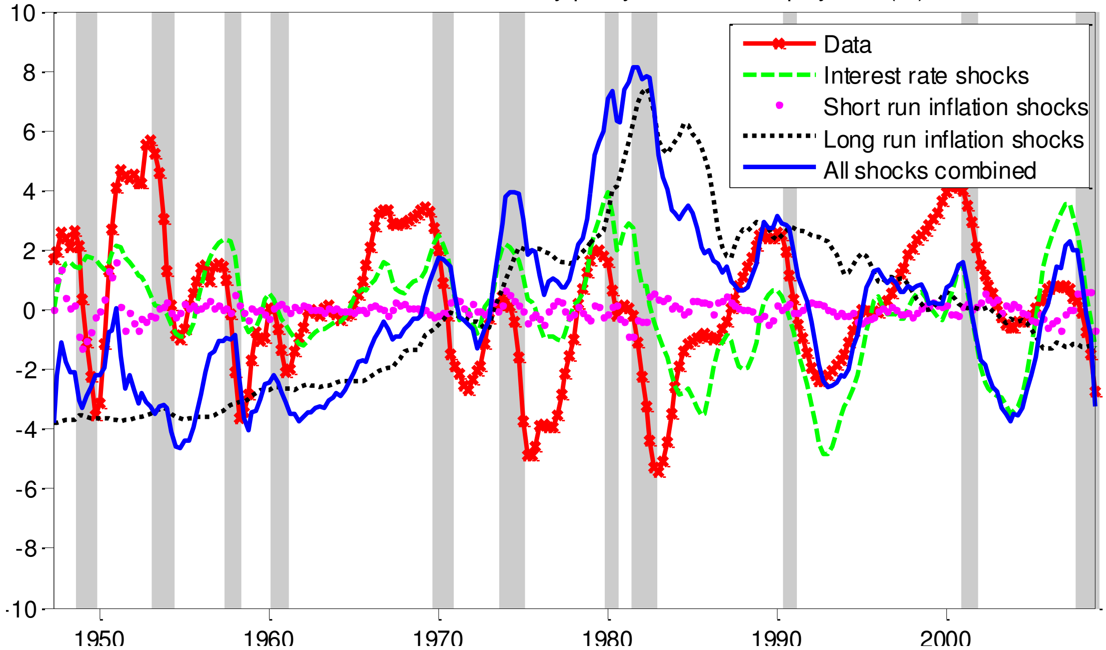
This figure shows the effects of the estimated shocks from 1947.III onward, when fed through the model. Gray lines indicate recessions.

Figure 5 – Effects of government and obs. shocks on employment.



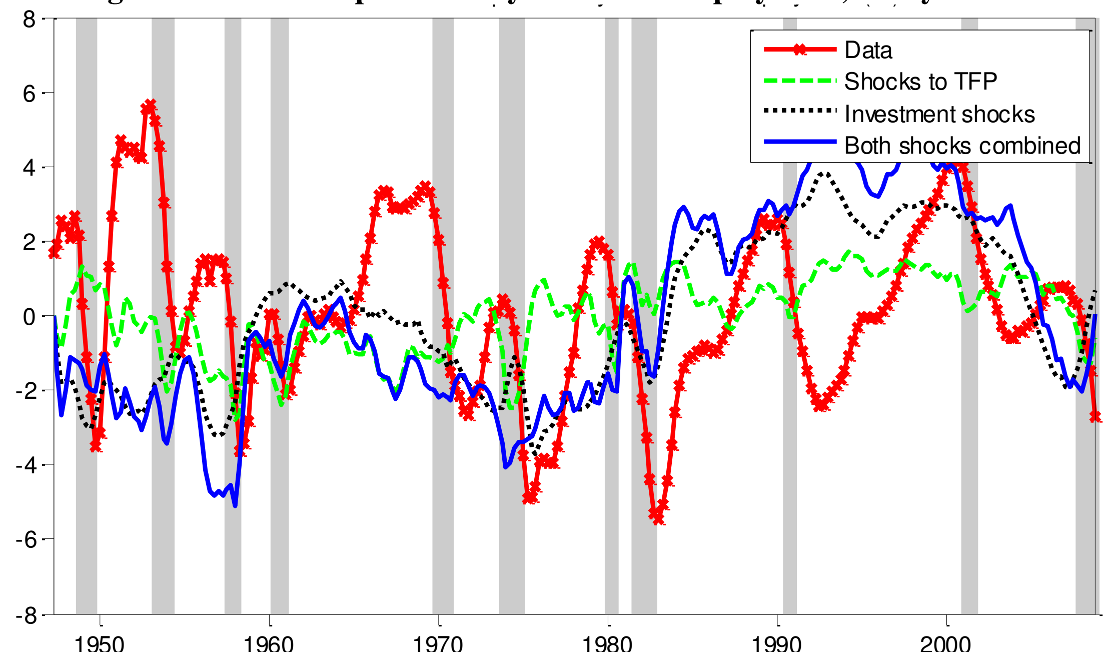
This figure shows the effects of the estimated shocks from 1947.III onward, when fed through the model. Gray lines indicate recessions.

Figure 6 – Effects of monetary shocks on employment, sticky model.



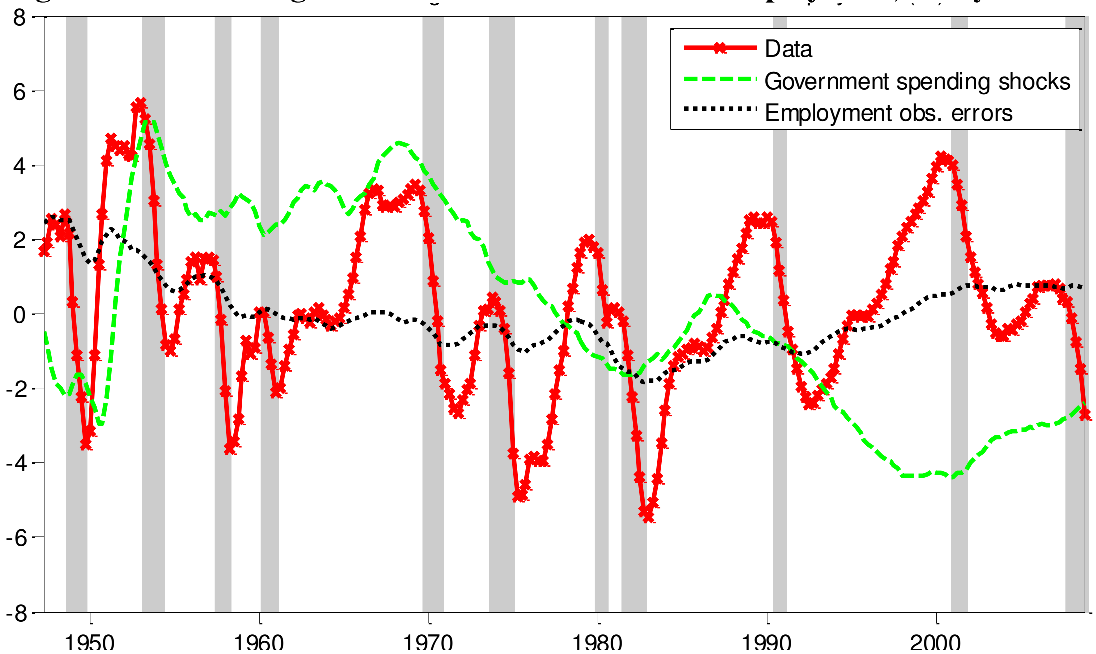
This figure shows the effects of the estimated shocks from 1947.III onward, when fed through the model. Gray lines indicate recessions.

Figure 7 –Effects of productivity shocks on employment, sticky model.



This figure shows the effects of the estimated shocks from 1947.III onward, when fed through the model. Gray lines indicate recessions.

Figure 8 – Effects of government and obs. shocks on employment, sticky model.



This figure shows the effects of the estimated shocks from 1947.III onward, when fed through the model. Gray lines indicate recessions.