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Policy Biases in a Model with Labor Market Frictions

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JEL Classification

E52, E61, C62, C73

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We develop a model with labor-market matching frictions that is subject to a range of shocks, including shocks to matching efficiency and bargaining power, and use the model to examine how monetary policy should respond to such shocks. We show that optimal monetary policy is highly efficient at responding to these labor market shocks, producing outcomes that are close to the flex-price equilibrium. Moreover, this efficiency remains if monetary policy is conducted with discretion, indicating that time-inconsistency and forward-guidance are not central to the policy response. We also show that several popular simple rules are also effective at responding to these labor market shocks.

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1 Introduction

The Great Recession represents a striking period in U.S. economic history. Not only did the economy fall into a recession whose depth was matched only by the great depression, causing nominal interest rates to fall to unprecedented levels and become constrained by an effective lower bound, but the labor market experienced great upheaval with vast numbers of workers needing to seek new employment. A well-documented feature of the Great Recession is that the unemployment rate, which peaked in October, 2009, was slow to subsequently decline, slow to return to a level broadly consistent with estimates of the natural rate of unemployment. In fact, although real GDP growth quickly bounced back to positive territory, the unemployment rate remained stubbornly high, taking until the second half of 2014 to fall below 6 percent. The economy's behavior during this period highlights the importance of labor market shocks and raises questions about how monetary policy ought to respond to such shocks, questions that are especially relevant in light of the current Covid-19 economic recession and the associated rise in unemployment.

Recent empirical work examining labor-market outcomes during the Great Recession has focused on search-and-matching frameworks and has highlighted the potential role of changes in matching efficiency and workers' bargaining power. For instance, Daly, Hobjin, Sahin, and Valletta (2012) use dispersion in job-growth across sectors and industries during the Great Recession to document a sustained decline in matching efficiency. Hall and Schukhofer-Wohl (2018) also document that matching efficiency fell during the Great Recession. They estimated the matching efficiency for heterogeneous job-seekers and concluded that although matching efficiency remained roughly constant for each group of job-seekers, the composition of job-seekers shifted towards groups with lower matching efficiency, leading to a decline in aggregate matching efficiency. Factors that have led to declines in worker bargaining power, including the Great Recession, are discussed in Krueger (2018), where the question of how central banks should respond to bargaining power shocks is raised.

Do shocks to matching efficiency and/or workers' bargaining power pose a big problem for a central bank? In the model we analyze, although matching efficiency shocks and bargaining power shocks produce important fluctuations in goods and labor markets, we find that these fluctuations are largely efficient and not due to a failure of monetary policy. Our results show that although a sustained decline in matching efficiency causes a rise in unemployment and a decline in production, that the economy's response to such a shock when monetary policy is set optimally tracks closely the flex-price equilibrium. Similarly, a sustained fall in workers' bargaining power leads to a decline in the real wage and to a rise in employment and hours worked, but again the responses when monetary policy is conducted optimal closely replicate those for the flex-price equilibrium.

We also ask how the efficiency with which optimal monetary policy responds to these shocks depends on the central bank being able to commit. Commitment facilitates a more efficient response to shocks because it enables the central bank to provide households, workers, and firms with forward guidance about future policy. We find that allowing monetary policy to be conducted with discretion rather than commitment has relatively little impact on how monetary policy responds. Thus, although discretion leads to an inflation bias, we do not find much evidence for a stabilization bias. Instead, the economy's responses to these shocks continues to closely track those for the flex-price equilibrium, suggesting that forward guidance—while potentially important in many contexts—is not an important factor in this model.

To provide counterpoints to optimal policy, we also examine how the economy responds to these shocks when monetary policy is conducted according to one of several simple rules. The first simple rule is a Taylor-type rule in which monetary policy responds to inflation and real output growth. The second simple rule is a Taylor-type rule in which policy responds to inflation and a measure of the "unemployment gap". The third simple rule is strict inflation targeting whereby monetary policy is conducted to keep inflation constant. Each of these simple rules is suboptimal, but our experiments show that their suboptimality is more evident in nominal variables and in the behavior of inflation and less evident in how the real economy behaves. In fact, although the Taylor-type rule that responded to the unemployment gap was the worst performing among the three simple rules, all three simple rules performed well, producing levels of household welfare that were close to that for the optimal monetary policy.

We undertake our analysis using a model that allows for several important rigidities and market imperfections. The model is one for which the goods market is characterized by monopolistic competition and sticky prices and the labor market is characterized by a matching friction and Nash-bargaining. Monopolistic competition and the matching friction render the flex-price equilibrium inefficient. The price-rigidity in the goods market offers a role for monetary policy, which we assume is conducted in order to maximize household welfare.

Collectively these frictions and rigidities open the door to both a discretionary inflation bias and a discretionary stabilization bias.

Although the effects of matching efficiency shocks and bargaining shocks are important to the analysis, our model also includes several other shocks, including consumption preference shocks, aggregate technology shocks, and shocks to the elasticity of substitution between goods. This latter shock governs the level of competition in the goods market and impacts the price markup that firms can charge. Our analysis of these shocks shows, with the exception of the elasticity of substitution shock, that optimal policy (assuming either commitment or discretion) leads to outcomes that closely track the flex-price economy, that there is little evidence for discretionary stabilization bias or a role for forward-guidance, and that the simple rules are remarkably effective in their response. Shocks to the elasticity of substitution do, however, pose a problem for the optimizing central bank, with the responses to this shock revealing discretionary stabilization bias. The simple rules also struggle to respond effectively to the elasticity of substitution shock.

We contribute to the macro-labor literature on search and matching by analyzing optimal monetary policy in a search-matching model while allowing for a range of shocks, including those to the matching efficiency and to worker bargaining power, which, although empirically relevant, have received relatively little attention in the monetary policy literature. In this dimension, our work is related to Furlanetto and Groshenny (2016) who estimate a Dynamic Stochastic General Equilibrium (DSGE) model that contains matching and bargaining power shocks for the U.S. Their model identifies a substantial decline in matching efficiency during the Great Recession. Zhang (2017) estimates a DSGE model for the U.S. that, similar to Furlanetto and Groshenny (2016), allows for a host of rigidities, market imperfections, and stochastic disturbances, including shocks to the matching efficiency and bargaining power. Where these two studies estimate log-linearized models and focus on the effect that various shocks have had on the natural rate of unemployment, we analyze a fully non-linear model that allows for level and stabilization biases. Moreover, we focus on how a welfare-maximizing central bank should optimally respond to labor-market shocks, and whether these shocks are an important source of policy biases.

We also contribute to the literature on optimal monetary policy and policy biases. It is well-known that monetary policy can lead to a discretionary inflation bias (Kydland and Prescott, 1977; Barro and Gordon, 1983) and/or to a discretionary stabilization bias (Svensson, 1997; Woodford, 1999), the magnitudes of which depend upon the shocks that hit the economy and their volatility, and on the extent to which steady state production is inefficient. For our model, we find that time-inconsistency leads to a pronounced discretionary inflation bias, but does not generally lead to a large stabilization bias. Thus, while we find an inflation bias of around two percent per annum, with the exception of shocks to the elasticity of substitution among goods, we find that commitment and discretion produce largely similar impulse response functions. Although this result may initially seem surprising, it is consistent with what Dennis and Söderström (2006) found for non-micro-founded New Keynesian models, and, at the same time, the result that elasticity of substitution shocks—closely related to markup shocks—do cause an important stabilization bias is consistent with conventional wisdom (as summarized in, say, Clarida, Galí, and Gertler (1999)).

The remainder of the paper is organized as follows. Section 2 introduces the model, describes the rigidities and frictions that characterize the goods and labor markets and details the decision problems that govern household and firm behavior. How monetary policy is conducted is the focus of section 3, which begins by analyzing a flex-price equilibrium and then derives the optimality conditions associated with the optimal commitment policy and the optimal discretionary policy. Section 4 presents the model's parameterization and discusses the literature upon which this parameterization is based. Simulation results and impulse responses for all five shocks pertaining to the flex-price equilibrium, the commitment equilibrium, and the discretionary equilibrium are presented and discussed in section 5. Section 6 introduces three non-optimized simple policy rules: strict inflation targeting and two Taylor-type rules that respond to output growth and the unemployment rate (in addition to inflation), respectively. Section 7 offers some concluding remarks.

2 The economy

We consider an economy populated by households, firms, a fiscal authority, and a central bank. Households consume a bundle of different goods and supply their labor to firms. Firms employ labor and sell their produce in a monopolistically competitive market. On the policy side, the central bank conducts policy by setting the short-term nominal interest rate in order to maximize household welfare. The fiscal authority pays unemployment benefits, financing this expenditure via a lump-sum tax. In this model, household-members can be either employed or unemployed. Firms post vacancies and hire workers through a matching market with the wage and the number of hours worked determined according to a Nash-bargaining scheme. Firms are price-setters, exploiting their monopolistic power to price as a markup over marginal costs while also facing a Rotemberg-style (Rotemberg, 1982) quadratic cost to changing prices. On the employment side, firms must pay a fixed cost per-period to post the vacancies needed to participate in the labor market. The model that we use expands upon those studied by Faia (2009), Blanchard and Galí (2010), and Ravenna and Walsh (2011) and is related to Furlanetto and Groshenny (2016) and Zhang (2017).

2.1 Households

Households consist of a unit-continuum of members that obtain utility from consumption and leisure. During period t, some proportion of the household's members are not employed $(1-n_t)$ and the remainder are employed (n_t), but insurance operates within the household so that all members receive the same consumption regardless of their employment status. Aggregating across those employed and those not-employed, expected discounted lifetime utility for the representative household is:

$$\mathrm{E}_0\left[\sum_{t=0}^{\infty}\beta^t\left(\zeta_t\frac{c_t^{1-\sigma}-1}{1-\sigma}+\chi n_t\frac{(1-h_t)^{1-\nu}-1}{1-\nu}\right)\right], \tag{1}$$

where $\beta\in(0,1)$ is the subjective discount factor, $\sigma\in(0,\infty)$ is the (inverse of the) elasticity of intertemporal substitution, $\chi>0$ is a weighting coefficient, and $\nu>0$ is the (inverse of the) leisure demand elasticity. In equation (1), c_t denotes (real) final-good consumption, h_t denotes hours worked by household members that are employed, and ζ_t represents a consumption preference shock. The consumption preference shock is assumed to obey:

$$\log\left(\zeta_{t+1}\right)=\rho_\zeta\log\left(\zeta_t\right)+\varepsilon_{\zeta t+1}, \tag{2}$$

where $\rho_\zeta\in(0,1)$ and $\varepsilon_{\zeta t}\sim i.i.d.\ N\left(0,\sigma_\zeta^2\right)$. For a given real wage, an increase in ζ_t leads to an increase in the demand for consumption goods and to a decrease in the demand for leisure.

Using w_t to denote the real wage and b to denote real unemployment benefits, members of the household that work generate real income equaling $w_th_tn_t$, while those not employed receive unemployment benefits and generate income equaling $b\left(1-n_t\right)$. In addition to income from working and income from benefits, the household receives income in the form of a dividend payment through its ownership of firms. Households can save by purchasing one-period nominal non-state contingent bonds, B_t, which pay a gross nominal interest rate equal to $1 + R_{t-1}$ and are in zero-net supply.

The household's flow budget constraint can be written as:

$$c_t + \frac{B_{t+1}}{P_t} + \tau_t = w_t h_t n_t + b\,(1 - n_t) + (1 + R_{t-1})\,\frac{B_t}{P_t} + d_t, \tag{3}$$

where d_t denotes real dividends and τ_t denotes lump-sum taxes.

Households choose $\{c_t, B_{t+1}\}_{t=0}^{\infty}$, taking the processes $\{P_t,\, w_t,\, R_t,\, D_t,\, \tau_t,\, n_t, h_t\}_{t=0}^{\infty}$ as given and the initial condition, B_0, as known, to maximize equation (1) subject to equation (3). The resulting first-order conditions can be combined and expressed in terms of the consumption-Euler equation:

$$c_t^{-\sigma} = \beta\,(1 + R_t)\,\mathrm{E}_t\left[\frac{P_t}{P_{t+1}}\frac{\zeta_{t+1}}{\zeta_t}c_{t+1}^{-\sigma}\right]. \tag{4}$$

There is no explicit labor supply choice because the level of hours worked is determined as part of the bargaining process with firms (Krause, Lopez-Salido, and Lubik, 2008a, 2008b).

2.2 Production

Wholesale good are produced by a unit-continuum of firms that hire new workers from a matching market. Unemployed workers must search for a job and to fill a vacant position firms must post a vacancy, incurring a fixed cost per-period to do so. Firms, and those employed, face an exogenous separation probability whereby matches are stochastically destroyed and workers become unemployed. Firms sell their goods in a monopolistically competitive market and choose their price subject to their demand curve and to a price-adjustment cost. Wages and hours worked are determined through a Nash bargaining process that takes place on an individual basis between workers and firms. Once produced, wholesale goods are combined in a retail sector into an aggregate good that is sold to households and the government.

2.2.1 Labor dynamics

The number of workers employed by the i'th firm, $i \in [0, 1]$, at the end of period $t-1$ is denoted $n_{t-1}(i)$. New jobs are created at the beginning of period t and some jobs are exogenously dissolved at the end of period t such that by the end of period t the i'th firm's employment level is:

$$n_t(i) = (1-\delta)\, n_{t-1}(i) + m_t(i), \tag{5}$$

where $\delta \in (0,1)$ is the exogenous separation rate and $m_t(i)$ represents the number of new jobs, or matches, formed between the pool of unemployed workers and firm i.

The total number of matches that occur economy-wide is governed by the constant-returns-to-scale matching technology:

$$M_t = m_t u_t^{\xi} v_t^{1-\xi}, \tag{6}$$

where v_t denotes the vacancy rate (also the economy-wide number of vacancies), u_t denotes the unemployment rate (also the size of the unemployment pool), $\xi \in (0,1)$ represents the elasticity of matches with respect to the unemployment rate, and m_t denotes the matching efficiency. Unemployed workers and firms that have posted vacancies meet randomly. The matching technology says that the number of matches formed is increasing in the number of vacancies and the number of unemployed workers, with the overall matching efficiency dictated by m_t. When m_t is high, matches can be formed more easily and vice-versa when m_t is low. The economy's matching efficiency is stochastic and follows the process:

$$\log\left(\frac{m_{t+1}}{m}\right) = \rho_m \log\left(\frac{m_t}{m}\right) + \varepsilon_{mt+1}, \tag{7}$$

where $m > 0$ determines the average matching efficiency, $\rho_m \in (0,1)$, and $\varepsilon_{mt} \sim$ *i.i.d.* $N\left(0, \sigma_m^2\right)$.

Following Mortensen and Pissarides (1994), we define the level of labor market tightness, θ_t, by:

$$\theta_t = \frac{v_t}{u_t}, \tag{8}$$

so that the labor market is tight (θ_t is high) when the size of the unemployment pool is small relative to the number of vacancies. Given the matching technology and the definition of labor market tightness, the economy's job-filling rate is:

$$q(\theta_t) = \frac{M_t}{v_t} = m_t \theta_t^{-\xi}, \tag{9}$$

and its job-finding rate is:

$$f(\theta_t) = \frac{M_t}{u_t} = m_t \theta_t^{1-\xi} = \theta_t q(\theta_t). \tag{10}$$

We assume that all firms take θ_t, $q(\theta_t)$, and $f(\theta_t)$ as given, and write equation (5) as:

$$n_t(i) = (1-\delta)\, n_{t-1}(i) + v_t(i)\, q(\theta_t), \tag{11}$$

where $v_t(i)$ is the number of vacancies posted by the i'th firm.

With economy-wide employment given by $n_t = \int_0^1 n_t(i)\, di$, the number of people that are unemployed at the start of period t is:

$$u_t = 1 - (1-\delta)\, n_{t-1}. \tag{12}$$

2.2.2 Firms

There is a unit-continuum of wholesale firms that produce according to the production technology:

$$y_t(i) = z_t h_t(i)\, n_t(i), \tag{13}$$

where z_t is an aggregate technology shock that is assumed to obey:

$$\log(z_{t+1}) = \rho_z \log(z_t) + \varepsilon_{zt+1}, \tag{14}$$

$\rho_z \in (0,1)$, and $\varepsilon_{zt} \sim i.i.d.\ N\left(0, \sigma_z^2\right)$. Equation (13) allows firms to increase production either by hiring more workers (extensive margin) or by increasing hours-worked (intensive margin). To hire more workers, firms must post a vacancy and pay a fixed cost for doing so. Firms are monopolistically competitive, choosing the price they charge for their good subject to the demand curve:

$$y_t(i) = \left(\frac{p_t(i)}{P_t}\right)^{-\epsilon_t} y_t, \tag{15}$$

where ϵ_t, the stochastic elasticity of substitution among goods, follows the process:

$$\log\left(\frac{\epsilon_{t+1}}{\epsilon}\right) = \rho_\epsilon \log\left(\frac{\epsilon_t}{\epsilon}\right) + \varepsilon_{\epsilon t+1}, \tag{16}$$

with $\epsilon > 1$, $\rho_\epsilon \in (0,1)$, and $\varepsilon_{\epsilon t} \sim i.i.d.\ N\left(0, \sigma_\epsilon^2\right)$. In equation (15), $p_t(i)$ denotes the price of the i'th firm's good, P_t denotes the aggregate price level, and y_t denotes aggregate output.

Taking $\{P_t, w_t, y_t, h_t(i)\}_{t=0}^\infty$ as given and with $p_{-1}(i)$ known, the decision confronting the i'th firm is to choose $\{p_t(i), n_t(i), v_t(i)\}_{t=0}^\infty$ to maximize:

$$\max_{\{p_t(i), n_t(i), v_t(i)\}_{t=0}^\infty} \mathrm{E}_0 \left[\sum_{t=0}^\infty \beta^t \frac{\lambda_t}{\lambda_0} \left(\begin{array}{c} \frac{p_t(i)}{P_t} y_t(i) - w_t h_t(i)\, n_t(i) - \kappa v_t(i) \\ -\frac{\psi}{2}\left(\frac{p_t(i)}{p_{t-1}(i)} - 1\right)^2 y_t \end{array} \right) \right], \tag{17}$$

where $\psi > 0$ governs the cost to changing prices, $\kappa > 0$ is the vacancy-posting cost, and $\lambda_t = \zeta_t c_t^{-\sigma}$ is the marginal utility of consumption in period t, subject to the production technology, equation (13), the demand curve, equation (15), and the law-of-motion for employment, equation (11).

The Lagrangian for this decision problem is:

$$\mathcal{L} = \mathrm{E}_0 \left[\sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left(\begin{array}{c} \left(\frac{p_t(i)}{p_t}\right)^{1-\epsilon_t} y_t - w_t h_t(i) n_t(i) - \kappa v_t(i) - \frac{\psi}{2}\left(\frac{p_t(i)}{p_{t-1}(i)} - 1\right)^2 y_t \\ -\mu_t \left(\left(\frac{p_t(i)}{P_t}\right)^{-\epsilon_t} y_t - z_t h_t(i) n_t(i) \right) \\ -\eta_t \left(n_t(i) - (1-\delta) n_{t-1}(i) - v_t(i) q(\theta_t) \right) \end{array} \right) \right], \quad (18)$$

where we used the demand curve (equation 15) to substitute for firm-level output and introduced two Lagrange multipliers: μ_t and η_t. The first of these Lagrange multipliers can be interpreted as the real marginal cost of production while the second represents the value to filling a vacancy.

Differentiating equation (18) with respect to $v_t(i)$, $p_t(i)$, and $n_t(i)$, respectively, and aggregating across firms we get the first-order conditions:

$$\kappa = \eta_t q(\theta_t), \quad (19)$$

$$\psi \pi_t (1 + \pi_t) = (1 - \epsilon_t + \epsilon_t \mu_t) + \beta \psi \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{y_{t+1}}{y_t} \pi_{t+1} (1 + \pi_{t+1}) \right], \quad (20)$$

$$\eta_t = h_t (\mu_t z_t - w_t) + \beta (1 - \delta) \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \eta_{t+1} \right], \quad (21)$$

where $\pi_t = \left(\frac{p_t}{p_{t-1}} - 1 \right)$ denotes the net inflation rate.

Equation (19) is the job-posting condition that says that firms will post vacancies up to the point where the expected payoff from filling a position equals the cost of posting the vacancy. Equation (20) describes optimal price setting and is in the form of an aggregate Phillips curve. Equation (21) is the job creation condition which says that the value of a filled position should equal the firm's current-period profit plus the discounted value of a filled position next period.

Before leaving this section, we note that the goods that the different firms produce are combined in a retail sector according to a constant-elasticity of substitution technology (Dixit and Stiglitz, 1977) into aggregate goods:

$$y_t = \left[\int_0^1 y_t(i)^{\frac{\epsilon_t - 1}{\epsilon_t}} di \right]^{\frac{\epsilon_t}{\epsilon_t - 1}}. \quad (22)$$

These aggregate goods are then sold in a perfectly competitive retail market to households and the government at the price:

$$P_t = \left[\int_0^1 p_t(i)^{1-\epsilon_t} \, di \right]^{\frac{1}{1-\epsilon_t}}. \tag{23}$$

As is well-known, retail firms make zero profits in equilibrium.

2.2.3 Wages and hours worked with Nash bargaining

The real wage and the number of hours worked are determined through Nash bargaining between workers and firms. Expressed in terms of period-t final goods, we denote using V_t^E and V_t^U the value to the household of having a member employed and unemployed, respectively.

The value to a household of having a member employed is given by:

$$V_t^E = w_t h_t + \chi \frac{(1-h_t)^{1-\nu} - 1}{(1-\nu)\lambda_t} + \beta \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \begin{pmatrix} \delta \left(1 - f(\theta_{t+1})\right) V_{t+1}^U \\ + \left(1 - \delta\left(1 - f(\theta_{t+1})\right)\right) V_{t+1}^E \end{pmatrix} \right]. \tag{24}$$

Looking at the terms on the right hand side of equation (24), the first term represents the extra goods that the household receives through the worker's labor income. The second term captures the value of the worker's leisure. The third term is a composite one that reflects the expected payoffs to being either unemployed or employed next period. For a worker that is employed today, the probability that they are unemployed next period is given by the separation rate, δ, multiplied by the probability that they are unable to be matched to a new job in period $t+1$, which equals one minus the job-filling rate. The payoff to being unemployed next period in terms of next-period goods is V_{t+1}^U. The next-period payoff to being employed next period equals V_{t+1}^E, which is multiplied by the probability of being employed. These next-period payoffs are multiplied by the marginal rate of substitution in order to be expressed in terms of period-t goods.

The value to the household of having a member unemployed is:

$$V_t^U = b + \beta \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \left(\left(1 - f(\theta_{t+1})\right) V_{t+1}^U + f(\theta_{t+1}) V_{t+1}^E \right) \right], \tag{25}$$

where the first term on the right hand side reflects the real benefits that accrue to being unemployed today and the second term is a composite one reflecting the expected payoffs to being unemployed or employed next period, which are then expressed in terms of period-t goods by multiplying by the marginal rate of substitution.

Now let $V_t^S = V_t^E - V_t^U$ denote the match surplus. Given equations (24) and (25), the match surplus for the household equals:

$$V_t^S = w_t h_t - b + \frac{\chi (1-h_t)^{1-\nu} - 1}{(1-\nu)\lambda_t} + \beta \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} (1-\delta)(1-f(\theta_{t+1})) V_{t+1}^S \right]. \tag{26}$$

Turning to the representative wholesale firm, the value of an unfilled vacancy, V_t^V, equals zero while the value of a filled vacancy, V_t^F, is given by equation (21). Recognizing that $V_t^F = \eta_t$ and making use of equation (19), we have:

$$V_t^F = h_t (\mu_t z_t - w_t) + \beta \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{(1-\delta)\kappa}{q(\theta_{t+1})} \right]. \tag{27}$$

The first term on the right hand side captures the real profits obtained from the goods produced from hiring an additional worker (filling a vacancy). The second term reflects the payoff that the firm receives when the match continues next period and the firm does not have to post a vacancy in order to fill a vacant position.

We assume that the real wage and hours worked are set by Nash bargaining with the worker's share of the joint surplus equal to ς_t, which is stochastic and obeys:

$$\log\left(\frac{\varsigma_{t+1}}{\varsigma}\right) = \rho_\varsigma \log\left(\frac{\varsigma_t}{\varsigma}\right) + \varepsilon_{\varsigma t+1}, \tag{28}$$

where $\rho_\varsigma \in (0,1)$ and $\varepsilon_{\varsigma t} \sim i.i.d.\ N\left(0, \sigma_\varsigma^2\right)$. Nash-bargaining leads to the well-known sharing rule:

$$V_t^S = \varsigma_t \left(V_t^S + V_t^F\right). \tag{29}$$

Substituting equations (26) and (27) and the one-period lead of equation (19) into equation (29) yields:

$$\begin{aligned} w_t h_t \;\; = \;\; & \varsigma_t \left(z_t h_t \mu_t + \beta (1-\delta) \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \left(1 - (1 - f(\theta_{t+1})) \frac{(1-\varsigma_t)\varsigma_{t+1}}{(1-\varsigma_{t+1})\varsigma_t} \right) \frac{\kappa}{q(\theta_{t+1})} \right] \right) \\ & + (1-\varsigma_t) \left(b - \frac{\chi}{\lambda_t} \frac{(1-h_t)^{1-\nu} - 1}{(1-\nu)} \right). \end{aligned} \tag{30}$$

Equations (10) and (9) allow equation (30) to be expressed as:

$$\begin{aligned} w_t h_t \;\; = \;\; & \varsigma_t \left(z_t h_t \mu_t + \beta (1-\delta) \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \left(1 - \left(1 - m_{t+1} \theta_{t+1}^{1-\xi}\right) \frac{(1-\varsigma_t)\varsigma_{t+1}}{(1-\varsigma_{t+1})\varsigma_t} \right) \frac{\kappa}{m_{t+1}\theta_{t+1}^{-\xi}} \right] \right) \\ & + (1-\varsigma_t) \left(b - \frac{\chi}{\lambda_t} \frac{(1-h_t)^{1-\nu} - 1}{(1-\nu)} \right), \end{aligned} \tag{31}$$

which determines the real wage per worker as a weighted average of the marginal revenue product of the worker plus the cost of replacing the worker and the outside option of the worker.

Finally, hours worked are chosen to maximize the joint surplus of the match, $V_t^S + V_t^F$, which gives:

$$\mu_t z_t = \chi \frac{(1-h_t)^{-\nu}}{\lambda_t}. \tag{32}$$

2.2.4 Fiscal policy

The fiscal authority finances its unemployment-benefit payments using lump-sum taxes. We assume that the fiscal authority cannot issue bonds and that its budget constraint is described by the balanced-budget condition:

$$b\,(1-n_t) = \tau_t. \tag{33}$$

3 Monetary policy

The key equations in the model, those that constrain policy and govern equilibrium outcomes, are equations (4), (8), (12), (19), (20), (21), (31), and (32). In addition, we have the resource constraint:

$$y_t = c_t + \kappa v_t + \frac{\psi}{2}\pi_t^2 y_t, \tag{34}$$

the law-of-motion for aggregate employment:

$$n_t = (1-\delta)\,n_{t-1} + v_t m_t \theta_t^{-\xi}, \tag{35}$$

and an equation for aggregate production:

$$y_t = z_t h_t n_t. \tag{36}$$

To reduce the number of constraints, we use equation (36) substitute for aggregate output, y_t, equation (12) to substitute for unemployment, u_t, equation (8) to substitute for vacancies, v_t, equation (31) to substitute for the real wage, w_t, and equation (32) to substitute for real marginal costs, μ_t. Setting the consumption Euler equation aside (it is used residually to solve for the nominal interest rate), these substitutions lead to the four-equation system:

$$\begin{aligned}
\psi\pi_t(1+\pi_t)\zeta_t c_t^{-\sigma} z_t h_t n_t &= (1-\epsilon_t)\zeta_t c_t^{-\sigma} z_t h_t n_t + \epsilon_t \chi (1-h_t)^{-\nu} h_t n_t \\
&\quad + \beta\psi \mathrm{E}_t\left[\zeta_{t+1} c_{t+1}^{-\sigma} z_{t+1} h_{t+1} n_{t+1} \pi_{t+1}(1+\pi_{t+1})\right], \qquad (37)\\
\frac{\kappa\zeta_t c_t^{-\sigma}}{(1-\varsigma_t) m_t \theta_t^{-\xi}} &= \chi\frac{(1-\nu h_t)(1-h_t)^{-\nu}-1}{1-\nu} - \zeta_t c_t^{-\sigma} b \\
&\quad + \beta(1-\delta)\mathrm{E}_t\left[\kappa\zeta_{t+1} c_{t+1}^{-\sigma}\frac{1-\varsigma_{t+1} m_{t+1}\theta_{t+1}^{1-\xi}}{(1-\varsigma_{t+1}) m_{t+1}\theta_{t+1}^{-\xi}}\right], \qquad (38)\\
z_t h_t n_t &= c_t + \kappa(1-(1-\delta)n_{t-1})\theta_t + \frac{\psi}{2}\pi_t^2 z_t h_t n_t, \qquad (39)\\
n_t &= (1-\delta)n_{t-1} + m_t(1-(1-\delta)n_{t-1})\theta_t^{1-\xi}, \qquad (40)
\end{aligned}$$

which reflect the firm's pricing decision in the form of a nonlinear Phillips curve (equation 37), the firm's employment decision (equation 38), the resource constraint (equation 39) and the law-of-motion for employment (equation 40).

We describe the decision problems associated with the commitment policy and the discretionary policy below. However, before doing so we present the conditions for the flex-price equilibrium.

3.1 Flex-price equilibrium

To better isolate the effect of the labor market frictions, we consider the equilibrium for the case where prices are flexible and bargaining is efficient. Repeating some equations for clarity, the decision problem for a benevolent planner is to choose $\{c_t, h_t, n_t, \theta_t\}_{t=0}^{\infty}$ to maximize:

$$\mathrm{E}_0\left[\sum_{t=0}^{\infty}\beta^t\left(\zeta_t\frac{c_t^{1-\sigma}-1}{1-\sigma} + \chi n_t\frac{(1-h_t)^{1-\nu}-1}{1-\nu}\right)\right], \qquad (41)$$

subject to the law-of-motion for aggregate employment:

$$n_t = (1-\delta)n_{t-1} + m_t(1-(1-\delta)n_{t-1})\theta_t^{1-\xi}, \qquad (42)$$

and the constraint:

$$\frac{\epsilon_t - 1}{\epsilon_t} z_t h_t n_t = c_t - b(1-n_t) + \tau_t + \kappa(1-(1-\delta)n_{t-1})\theta_t. \qquad (43)$$

The first-order conditions from this planner's problem give rise to the following equation for hours worked:

$$\frac{\epsilon_t - 1}{\epsilon_t} z_t = \chi\frac{(1-h_t)^{-\nu}}{\zeta_t c_t^{-\sigma}}, \qquad (44)$$

and the equilibrium law-of-motion for labor market tightness:

$$\begin{aligned} \frac{\kappa\zeta_t c_t^{-\sigma}}{(1-\xi)\, m_t \theta_t^{-\xi}} &= \chi\frac{(1-\nu h_t)(1-h_t)^{-\nu}-1}{1-\nu} - \zeta_t c_t^{-\sigma} b \\ &\quad +\beta(1-\delta)\,\mathrm{E}_t\left[\kappa\zeta_{t+1}c_{t+1}^{-\sigma}\frac{1-\xi m_{t+1}\theta_{t+1}^{1-\xi}}{(1-\xi)\, m_{t+1}\theta_{t+1}^{-\xi}}\right]. \end{aligned} \tag{45}$$

Equations (44) and (45) differ from equations (32) and (38) in a couple of respects. First, comparing equations (32) and (44), in the flex-price equilibrium real marginal costs are equal to $\frac{\epsilon_t-1}{\epsilon_t}$. Second, comparing equations (38) and (45), the two equations are equivalent when:

$$\varsigma_t = \xi. \tag{46}$$

Equation (46) is the Hosios condition (Hosios, 1990) which states that efficient bargaining requires workers' bargaining power to be constant and to equal the share of unemployment in the matching function. When workers' bargaining power is too low, $\varsigma_t < \xi$, firms make profits from a match which leads to excessive vacancy posting and to an inefficiently low unemployment rate. Similarly, when workers have too much bargaining power, $\varsigma_t > \xi$, firms have insufficient incentive to post vacancies and the unemployment rate is inefficiently high.

3.2 Commitment (Ramsey) equilibrium

Under the commitment policy the central bank chooses $\{\pi_t\}_{t=0}^{\infty}$ to maximize household welfare (equation 41) subject to equations (37)—(40). Expressing the central bank's decision problem in the form of a Lagrangian:

$$\mathcal{L} = \mathrm{E}_0\sum_{t=0}^{\infty}\beta^t\left(\begin{array}{c} \zeta_t\frac{c_t^{1-\sigma}-1}{1-\sigma}+\chi n_t\frac{(1-h_t)^{1-\nu}-1}{1-\nu} \\ +\phi_{1t}\left(\begin{array}{c}(1-\epsilon_t)\,\zeta_t c_t^{-\sigma}z_t h_t n_t+\epsilon_t\chi(1-h_t)^{-\nu}h_t n_t \\ +\beta\psi\zeta_{t+1}c_{t+1}^{-\sigma}z_{t+1}h_{t+1}n_{t+1}\pi_{t+1}(1+\pi_{t+1}) \\ -\psi\pi_t(1+\pi_t)\,\zeta_t c_t^{-\sigma}z_t h_t n_t\end{array}\right) \\ +\phi_{2t}\left(\begin{array}{c}\chi\frac{(1-\nu h_t)(1-h_t)^{-\nu}-1}{1-\nu}-\zeta_t c_t^{-\sigma}b \\ +\beta(1-\delta)\,\kappa\zeta_{t+1}c_{t+1}^{-\sigma}\frac{1-\varsigma_{t+1}m_{t+1}\theta_{t+1}^{1-\xi}}{(1-\varsigma_{t+1})m_{t+1}\theta_{t+1}^{-\xi}} \\ -\frac{\kappa\zeta_t c_t^{-\sigma}}{(1-\varsigma_t)m_t\theta_t^{-\xi}}\end{array}\right) \\ +\phi_{3t}\left(c_t+\kappa(1-(1-\delta)\,n_{t-1})\,\theta_t+\frac{\psi}{2}\pi_t^2 z_t h_t n_t - z_t h_t n_t\right) \\ +\phi_{4t}\left((1-\delta)\,n_{t-1}+m_t(1-(1-\delta)\,n_{t-1})\,\theta_t^{1-\xi}-n_t\right)\end{array}\right), \tag{47}$$

where ϕ_{1t}—ϕ_{4t} denote the Lagrange multipliers on equations (37)—(40), respectively, the first-order conditions are:

$$
\begin{aligned}
\frac{\partial \mathcal{L}}{\partial \pi_t} &: \pi_t \phi_{3t} - (1+2\pi_t)\zeta_t c_t^{-\sigma}\left(\phi_{1t} - \phi_{1t-1}\right) = 0, && (48) \\
\frac{\partial \mathcal{L}}{\partial c_t} &: c_t + \sigma(\epsilon_t - 1) z_t h_t n_t \phi_{1t} + \sigma\psi\pi_t(1+\pi_t) z_t h_t n_t \left(\phi_{1t} - \phi_{1t-1}\right) \\
&: \sigma b \phi_{2t} + \sigma\kappa \frac{\phi_{2t} - (1-\delta)\left(1 - \varsigma_t m_t \theta_t^{1-\xi}\right)\phi_{2t-1}}{(1-\varsigma_t) m_t \theta_t^{-\xi}} + \frac{c_t^{\sigma+1}}{\zeta_t}\phi_{3t} = 0, && (49) \\
\frac{\partial \mathcal{L}}{\partial h_t} &: -\chi n_t (1-h_t)^{-\nu} + \nu\chi h_t (1-h_t)^{-\nu-1}\phi_{2t} + \left(\frac{\psi}{2}\pi_t^2 - 1\right) z_t n_t \phi_{3t} \\
&: +\left((1-\epsilon_t - \psi\pi_t(1+\pi_t))\zeta_t c_t^{-\sigma} z_t + \epsilon_t \chi (1-(1-\nu)h_t)(1-h_t)^{-\nu-1}\right) n_t \phi_{1t} \\
&: +\psi\zeta_t c_t^{-\sigma} z_t n_t \pi_t (1+\pi_t)\phi_{1t-1} = 0, && (50) \\
\frac{\partial \mathcal{L}}{\partial n_t} &: \chi\frac{(1-h_t)^{1-\nu} - 1}{1-\nu} + \left((1-\epsilon_t - \psi\pi_t(1+\pi_t))\zeta_t c_t^{-\sigma} z_t + \epsilon_t\chi(1-h_t)^{-\nu}\right) h_t \phi_{1t} \\
&: -\phi_{4t} + \left(\frac{\psi}{2}\pi_t^2 - 1\right) z_t h_t \phi_{3t} + \psi\pi_t(1+\pi_t)\zeta_t c_t^{-\sigma} z_t h_t \phi_{1t-1} \\
&: +\beta(1-\delta)\,\mathrm{E}_t\left[\left(1 - m_{t+1}\theta_{t+1}^{1-\xi}\right)\phi_{4t+1} - \kappa\theta_{t+1}\phi_{3t+1}\right] = 0, && (51) \\
\frac{\partial \mathcal{L}}{\partial \theta_t} &: -\frac{\kappa\zeta_t c_t^{-\sigma}\xi\theta_t^{\xi-1}}{(1-\varsigma_t) m_t}\phi_{2t} + (1-\delta)\kappa\zeta_t c_t^{-\sigma}\frac{\xi\theta_t^{\xi-1} - \varsigma_t m_t}{(1-\varsigma_t) m_t}\phi_{2t-1} \\
&: +\kappa(1-(1-\delta)n_{t-1})\phi_{3t} + (1-\xi) m_t \theta_t^{-\xi}(1-(1-\delta)n_{t-1})\phi_{4t} = 0. && (52)
\end{aligned}
$$

To compute the commitment equilibrium we solve equations (37)—(40) and (48)—(52) with the initial conditions that the first and second Lagrange multipliers equal zero in period -1.

3.3 Discretionary equilibrium

To simplify notation, let $\mathbf{s}_t = \begin{bmatrix} z_t & m_t & \varsigma_t & \zeta_t & \epsilon_t \end{bmatrix}'$. The Lagrangian for the optimal discretionary policy is:[1]

[1] An alternative equivalent approach is to formulate the decision problem in terms of a Bellman equation and then exploit the Benveniste-Scheinkman condition.

$$\mathcal{L} = \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\begin{array}{c} \zeta_t \frac{c_t^{1-\sigma}-1}{1-\sigma} + \chi n_t \frac{(1-h_t)^{1-\nu}-1}{1-\nu} \\ +\phi_{1t} \left(\begin{array}{c} (1-\epsilon_t)\,\zeta_t c_t^{-\sigma} z_t h_t n_t + \epsilon_t \chi \,(1-h_t)^{-\nu} h_t n_t \\ +\beta\psi F\,(n_t, \mathbf{s}_{t+1}) - \psi\pi_t\,(1+\pi_t)\,\zeta_t c_t^{-\sigma} z_t h_t n_t \end{array} \right) \\ +\phi_{2t} \left(\begin{array}{c} \chi \frac{(1-\nu h_t)(1-h_t)^{-\nu}-1}{1-\nu} - \zeta_t c_t^{-\sigma} b \\ +\beta\,(1-\delta)\,G\,(n_t, \mathbf{s}_{t+1}) - \frac{\kappa\zeta_t c_t^{-\sigma}}{(1-\varsigma_t) m_t \theta_t^{-\xi}} \end{array} \right) \\ +\phi_{3t} \left(c_t + \kappa\,(1-(1-\delta)\,n_{t-1})\,\theta_t + \frac{\psi}{2}\pi_t^2 z_t h_t n_t - z_t h_t n_t \right) \\ +\phi_{4t} \left((1-\delta)\,n_{t-1} + m_t\,(1-(1-\delta)\,n_{t-1})\,\theta_t^{1-\xi} - n_t \right) \end{array} \right), \tag{53}$$

where expected future variables are expressed as functions of the state variables:

$$\begin{aligned} F\,(n_t, \mathbf{s}_{t+1}) &= \mathrm{E}_t \left[\zeta_{t+1} c_{t+1}^{-\sigma} z_{t+1} h_{t+1} n_{t+1} \pi_{t+1}\,(1+\pi_{t+1}) \right], & (54) \\ G\,(n_t, \mathbf{s}_{t+1}) &= \mathrm{E}_t \left[\kappa\zeta_{t+1} c_{t+1}^{-\sigma} \frac{1-\varsigma_{t+1} m_{t+1} \theta_{t+1}^{1-\xi}}{(1-\varsigma_{t+1})\,m_{t+1}\theta_{t+1}^{-\xi}} \right]. & (55) \end{aligned}$$

The first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial \pi_t} : \pi_t \phi_{3t} - (1+2\pi_t)\,\zeta_t c_t^{-\sigma} \phi_{1t} = 0, \tag{56}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial c_t} &: \; c_t + \sigma\,((\epsilon_t - 1)\,z_t h_t n_t + \psi\pi_t\,(1+\pi_t)\,z_t h_t n_t)\,\phi_{1t} \\ &: \; + \left(\sigma b + \frac{\sigma\kappa}{(1-\varsigma_t)\,m_t\theta_t^{-\xi}} \right) \phi_{2t} + \frac{c_t^{\sigma+1}}{\zeta_t} \phi_{3t} = 0, & (57) \\ \frac{\partial \mathcal{L}}{\partial h_t} &: \; -\chi n_t\,(1-h_t)^{-\nu} + \nu\chi h_t\,(1-h_t)^{-\nu-1} \phi_{2t} + \left(\frac{\psi}{2}\pi_t^2 - 1 \right) z_t n_t \phi_{3t} \\ &: \; + \left((1-\epsilon_t - \psi\pi_t\,(1+\pi_t))\,\zeta_t c_t^{-\sigma} z_t + \epsilon_t \chi\,(1-(1-\nu)\,h_t)\,(1-h_t)^{-\nu-1} \right) n_t \phi_{1t} = 0, & (58) \\ \frac{\partial \mathcal{L}}{\partial n_t} &: \; \left((1-\epsilon_t - \psi\pi_t\,(1+\pi_t))\,\zeta_t c_t^{-\sigma} h_t z_t + \epsilon_t \chi\,(1-h_t)^{-\nu} h_t + \beta\psi \mathrm{E}_t F_1\,(n_t, \mathbf{s}_{t+1}) \right) \phi_{1t} \\ &: \; +\beta\,(1-\delta)\,\mathrm{E}_t G_1\,(n_t, \mathbf{s}_{t+1})\,\phi_{2t} + \left(\frac{\psi}{2}\pi_t^2 - 1 \right) z_t h_t \phi_{3t} - \phi_{4t} + \chi \frac{(1-h_t)^{1-\nu}-1}{1-\nu} \\ &: \; +\beta\,(1-\delta)\,\mathrm{E}_t \left[\left(1 - m_{t+1}\theta_{t+1}^{1-\xi} \right) \phi_{4t+1} - \kappa\theta_{t+1}\phi_{3t+1} \right] = 0, & (59) \\ \frac{\partial \mathcal{L}}{\partial \theta_t} &: \; -\frac{\kappa\zeta_t c_t^{-\sigma} \xi \theta_t^{\xi-1}}{(1-\varsigma_t)\,m_t} \phi_{2t} + \kappa\,(1-(1-\delta)\,n_{t-1})\,\phi_{3t} + (1-\xi)\,m_t \theta_t^{-\xi}\,(1-(1-\delta)\,n_{t-1})\,\phi_{4t} = 0 & (60) \end{aligned}$$

We compute the discretionary policy by solving equations (54)—(60) together with the constraints, equations (37)—(40).

4 Parameterization

We assume that the length of a period is one quarter of a year and parameterize the model to this frequency. Consistent with many other studies, we set the discount factor, β, to 0.99, implying an annualized steady state real interest rate of 4 percent. The elasticity of intertemporal substitution is set to one, $\sigma = 1$, which implies that household utility depends on the log of consumption. Furlanetto and Groshenny (2016) also set $\sigma = 1$, as do Gertler, Sala, and Trigari (2008). Our model allows for labor to adjust along both the extensive and intensive margins. Taking into account that much labor-market adjustment occurs at the extensive margin (see Prescott (2004) and the discussion in Christiano, Trabandt, and Walentin (2011)), we set ν to 5.0 and then choose χ such that hours worked equal 0.4 on average, i.e., that those with jobs work 40 percent of their available time. It follows that the labor supply elasticity that reflects only changes in hours worked (i.e., only the intensive margin) is low at about 0.12 and that χ equals 0.2.

We set ϵ to 11.0, which gives a steady state mark up of 10 percent. This markup is the same as Krause, López-Salido, and Lubik (2008a), Dennis (2018), Zhang (2017), and is consistent with Basu and Fernald (1997). Other recent studies have set ϵ to 21.0 (Fernández-Villarerde et al, 2015; Krause, López-Salido, and Lubik, 2008b) or 6.0 (Christiano, Eichenbaum, and Evans, 2005, Campolmi and Gnocchi, 2016, Furlanetto and Groshenny, 2016), implying much smaller and much larger steady-state markups, respectively. However we found that these values for ϵ gave implausible values for steady state inflation. The quadratic cost to adjusting prices, ψ, is set to 80.0, based on the estimate in Ireland (2001). Our chosen value for ψ lies comfortably between the 59.1 value estimated by Gavin, et al, (2015) and the 100.0 value estimated by Gust, et al, (2017).

There are tight cross-equation restrictions linking the structural parameters in the labor market. In particular, the job-finding rate, unemployment rate and the separation rate are related according to $f = \frac{\delta(1-u)}{u(1-\delta)}$, which yields the steady state employment rate $n = \frac{uf}{\delta}$. We choose to parameterize the separation rate and the job-finding rate in order to target the observable employment rate n and a measure of searching workers, u. Empirical estimates of the quarterly separation rate, δ, vary from 0.032 (Den Haan et. al. 2000) to 0.15 (Andolfatto, 1996). Shimer (2005) reports a 3.5% monthly separation rate. Based on these estimates, and consistent with Blanchard and Galí (2010) and Campolmi and Gnocchi (2016), we set $\delta = 0.12$.

Turing to the job-finding rate, Shimer (2005) reports a monthly job-finding rate of 0.45, which suggests a quarterly value for f of about 0.83 (assuming that the job, once found, is not lost again during the quarter). Ravenna and Walsh (2011) argue that the quarterly job-finding rate is about 0.7. Faia (2008) and Walsh (2005) assume that the quarterly job-finding rate is about 0.6. Drawing on these studies, we set $f = 0.65$. Our parameterization of δ and f deliver an employment rate of close to 0.94, and suggests that about 6.0 percent of the labor force is out-of-work during the period, which is broadly consistent with U.S. data. Our parameterization also implies that about 17 percent of the labor force ($u = 0.17$) are "searching workers", workers that are actively looking for jobs at the start of the period.

Following Shimer (2005) we set the elasticity of the matching function, ξ, to 0.72, and we utilize Hosios' condition (Hosios, 1990) and set worker's (mean) bargaining power, ς, to ξ. We have analyzed versions of the model where Hosios' condition does not hold and found that it had little effect on our results. In the matching technology, we set the average matching efficiency, m, to 0.66 which yields a mean job-filling rate of $q = m\theta^{-\xi} \approx 0.67$ with average labor market tightness, θ, equal to about 0.97. Finally, we parameterize b such that the steady state replacement ratio, $b/(wh)$ equals 0.2, which lies between the estimates of 0.12 and 0.36 found by Hall (2006) and Anderson and Meyer (1997), respectively, and κ so that the cost of posting a vacancy equals 20 percent of a worker's quarterly wage-income, i.e., $\kappa/(wh) = 0.2$, as per Ljungqvist (2002).

The full parameterization is reported in Table 1.

Table 1: Model Parameters

Intertemporal elasticity	σ	1.00	Matching efficiency	m	0.66
Discount factor	β	0.99	Vacancy elast. of matches	ξ	0.72
Elasticity of substitution	ϵ	11.0	Unemployment benefit	b	0.07
Price adj. cost	ψ	80.0	Cost of posting vacancy	κ	0.06
Separation rate	δ	0.12	Disutility of labor	χ	0.20
Workers bargaining power	ς	0.72	Elasticity of labor supply	ν	5.00
Shock Processes					
Shock	Persistence			Volatility	
Technology	ρ_a	0.95		σ_a	0.008
Matching efficiency	ρ_m	0.80		σ_m	0.032
Bargaining power	ρ_ζ	0.80		σ_ζ	0.028
Consumption preference	ρ_ξ	0.70		σ_a	0.006
Elasticity of substitution	ρ_ϵ	0.85		σ_ϵ	0.120

There are five shocks in the model: those to aggregate technology, a_t, the matching efficiency, m_t, worker bargaining power, ζ_t, consumption preferences, ξ_t, and the elasticity of substitution among goods, ϵ_t. Each shock $s \in \{a, m, \zeta, \xi, \epsilon\}$ is assumed to follow an AR(1) process with standard deviation σ_s and persistence parameter ρ_s, which are parameterized as follows.

For the aggregate technology shock, we follow convention (see Faia (2008) and the references therein) and set the persistence parameter, ρ_a, to 0.95 and the standard deviation for the technology innovation, σ_a, to 0.008. To parameterize the matching efficiency shock we set the persistence, ρ_m, to 0.8 and the standard deviation, σ_m, to 0.032, drawing upon the estimates in Sedlacek (2014), Furlanetto and Groshenny (2016), and Zhang (2017). With regard to the bargaining power shock, Ravenna and Walsh (2012) calibrate it based on output's volatility under optimal monetary policy with price stability leading them to choose $\rho_\zeta = 0.8$ and $\sigma_\zeta = 0.03$. We follow their approach and parametrize the bargaining shock by setting $\rho_\zeta = 0.80$ and $\sigma_\zeta = 0.028$, noting that Gertler, Sala, and Trigari (2008) obtain a smaller standard deviation: $\sigma_\zeta = 0.005$ while Furlanetto and Groshenny (2016) obtain a lower estimate for ρ_ζ (0.18).

We parameterize the consumption preference shock by setting $\rho_\xi = 0.7$ and $\sigma_\xi = 0.006$. These values are generally in the mid-range of other studies; for example Ichiue, Kurozumi, and Sunakawa (2013) find $\rho_\xi = 0.56$ and $\sigma_\xi = 0.0786$, Smets and Wouters (2003) estimate $\rho_\xi = 0.88$ and $\sigma_\xi = 0.003$, and Sala, Soderstrom, and Trigari (2008) estimate $\rho_\xi = 0.7$ and $\sigma_\xi = 0.0036$. Finally, for the elasticity of substitution shock, ϵ_t, estimates vary widely across studies. For example, Gertler, Sala, and Trigari (2008) estimate ρ_ϵ and σ_ϵ to be 0.81 and 0.008, Smets and Wouters (2007) estimate them to be 0.89 and 0.1, and Furlanetto and Groshenny (2016) obtain $\rho_\epsilon = 0.93$ and $\sigma_\epsilon = 0.055$. We set ρ_ϵ and σ_ϵ to 0.85 and 0.12, respectively, implying that 90 percent of the distribution of ϵ_t lies in the the interval $[7.56, 16.03]$.

5 Results

For the parameterization given in Table 1, we solve the model for the discretionary equilibrium, the commitment equilibrium, and the flex-price equilibrium. We use these solutions to simulate data and to compute the impulse response functions for each of the five shocks. The impulse response functions are discussed in the subsections below; Table 2 reports the deterministic steady state (as a reference point) and mean outcomes for the model's main variables.

Looking at the flex-price equilibrium first, Table 2 shows that the model's parameterization delivers a deterministic steady state value for the unemployment rate of about 5.95%, with this rate rising slightly to a mean value of about 6.04% in the stochastic economy. Supporting this unemployment rate is a job market in which about 17.5 percent of firms are posting vacancies each period and about 18 percent of the labor force are searching for jobs each period. Both the vacancy rate and the searching rate decline slightly in the stochastic model, leaving the mean value for labor market tightness equal to about 0.97. Consistent with the model's benchmark parameterization, the flex-price model delivers an annualized real interest rate of just over 4% p.a. and has workers spending about 40 percent of their time in production activities.

Table 2: Steady State and Simulation Outcomes

	Flex-price		Discretion	Commitment
Variable	Steady state	Mean (s.d.)	Mean (s.d.)	Mean (s.d.)
Output	0.3732	0.3728 (0.0110)	0.3730 (0.0109)	0.3729 (0.0109)
Consumption	0.3631	0.3627 (0.0105)	0.3626 (0.0105)	0.3628 (0.0105)
Hours worked	0.3968	0.3966 (0.0025)	0.3968 (0.0022)	0.3967 (0.0022)
Employment	0.9405	0.9396 (0.0120)	0.9397 (0.0119)	0.9397 (0.0119)
Unemployment rate (%)	5.9470	6.0377 (1.1985)	6.0253 (1.1902)	6.0283 (1.1885)
Searching rate (%)	17.9470	17.3132 (1.0547)	17.3022 (1.0474)	17.3049 (1.0459)
Vacancy rate (%)	17.4579	16.7188 (2.5113)	16.7473 (2.4758)	16.7374 (2.4571)
Tightness	0.9727	0.9717 (0.1715)	0.9738 (0.1689)	0.9731 (0.1681)
Real wage	0.8802	0.8783 (0.0310)	0.8791 (0.0296)	0.8791 (0.0296)
Real interest rate (% p.a.)	4.0404	4.0219 (1.2701)	4.0220 (1.2534)	4.0246 (1.3745)
Inflation rate (% p.a.)	—	—	1.8168 (0.7767)	0.0006 (0.3739)
Nominal interest rate (% p.a.)	—	—	5.8592 (1.5552)	4.0260 (1.3079)

If we look now at the mean outcomes for the discretion and commitment equilibria, several interesting results stand out. First, other than the large difference in the mean and volatility of inflation that is associated with the discretionary inflation and stabilization bias, which in turn are reflected in the nominal interest rate, the mean outcomes under discretion and commitment are very similar. Moreover, outcomes under discretion and commitment are very similar to those for the flex-price equilibrium. This results suggests that optimal policy—particularly commitment policy—is very efficient at responding to shocks in the model such that the resulting equilibrium outcomes are very similar to flex-price outcomes. Second, the model's discretionary inflation bias generates an annualized inflation rate of about 1.82% p.a., a rate that is substantial, but not implausible. Third, the absence of capital (or another asset that can be accumulated) from the model means that households do not respond to increased volatility with precautionary saving. Instead, households avoid the risk the shocks generate by substituting away from labor and towards leisure. Thus, mean outcomes for hours worked, employment, output, consumption, and the real wage are all lower in the stochastic economies relative to the deterministic steady state.

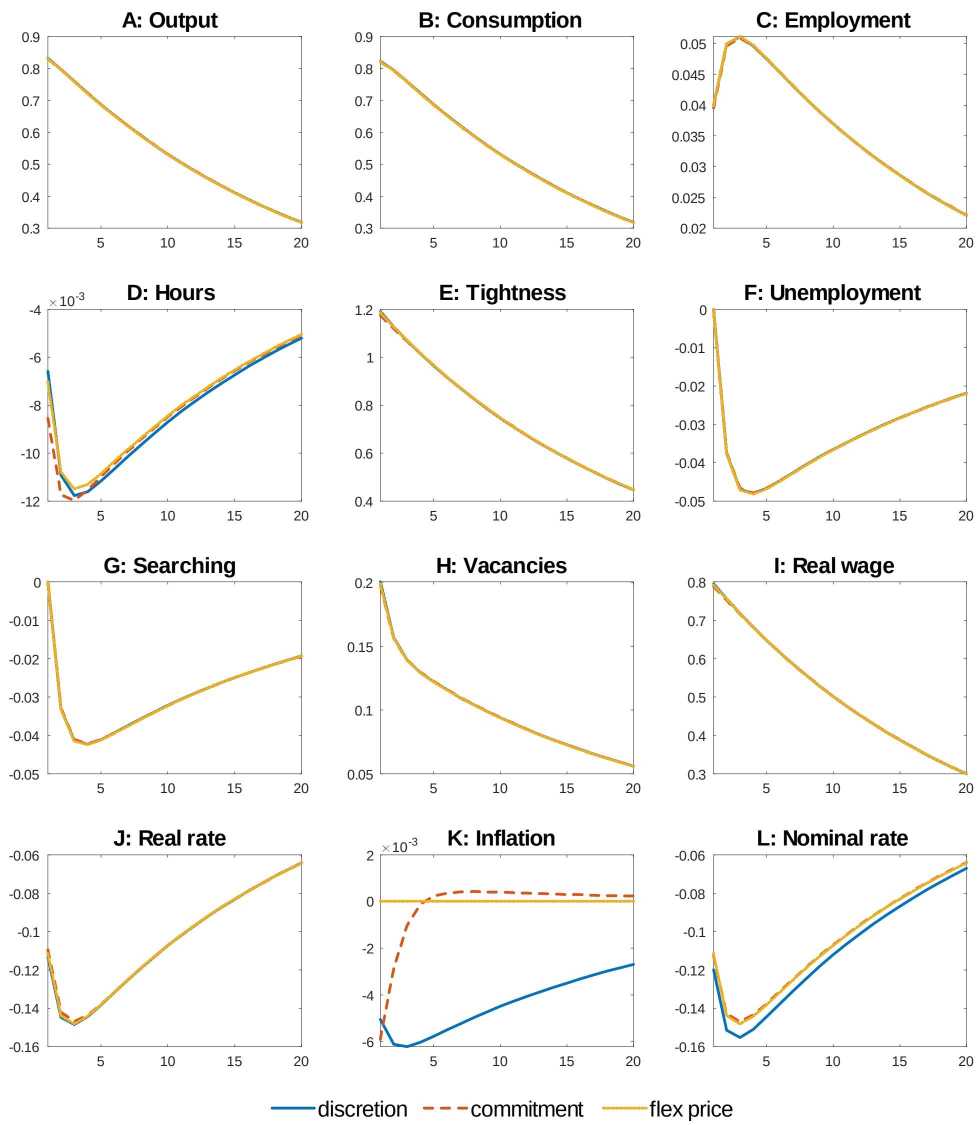

Fig. 1: Impulse responses to a positive 1 s.d. aggregate technology shock.

5.1 Productivity shock

Figure 1 illustrates the model's impulses responses following a positive one standard deviation aggregate productivity shock. On impact, higher aggregate productivity means that firms can produce more output from existing outputs. At the same time, worker productivity rises, which induces firms to post more vacancies (panel H) in an effort to increase hiring. Higher vacancies leads to a rise in employment (panel C), a decline in unemployment (panel F), and a rise to labor market tightness (panel E), which brings about a rise in the real wage (panel I). With output already boosted because of higher technology, the increase in employment gives rise to a further increase in output (panel A).

Higher output reflects higher household income. Households respond to the temporarily higher income by increasing their consumption (panel B) and by raising their demand for bonds, which generates a decline in the real interest rate (panel J). The rise in aggregate technology also has the effect of lowering firm's real marginal costs, which feeds into lower inflation (panel K). With both the real interest rate and inflation falling in response to the technology shock, the nominal interest rate also falls (panel L).

As time passes the pressures on the labor market dissipate and the impulses responses return to zero. However, the dynamic adjustments are relatively slow with only about 50 percent of the adjustment completed after five years (20 quarters). The adjustment process involves hump-shaped responses for employment, and the real and nominal interest rates, but not for consumption or output, which tend to decay geometrically in line with the technology process.

The discussion above has not distinguished among the flex-price responses, the discretion responses, and the commitment responses. This is because, despite the potential for a discretionary stabilization bias, the responses for all three equilibria behave very similarly, suggesting that both commitment policy and discretionary policy generally do a good job of replicating the flex-price equilibrium for this shock. However, some differences among them are evident in the behavior of inflation and the nominal interest rate. Although there is no meaningful concept of inflation in the flex-price equilibrium, the inflation responses under commitment and discretion illustrate standard behavior (Woodford, 2003). Under commitment, promises of higher future inflation mean that the short-run decline in inflation is relatively short-lived, and the period of negative inflation is following by a period of positive inflation leaving the price level unchanged in the long-run. In contrast, under discretion the decline in inflation is much longer-lived and inflation returns to zero from below leaving the price level permanently lower following the shock.

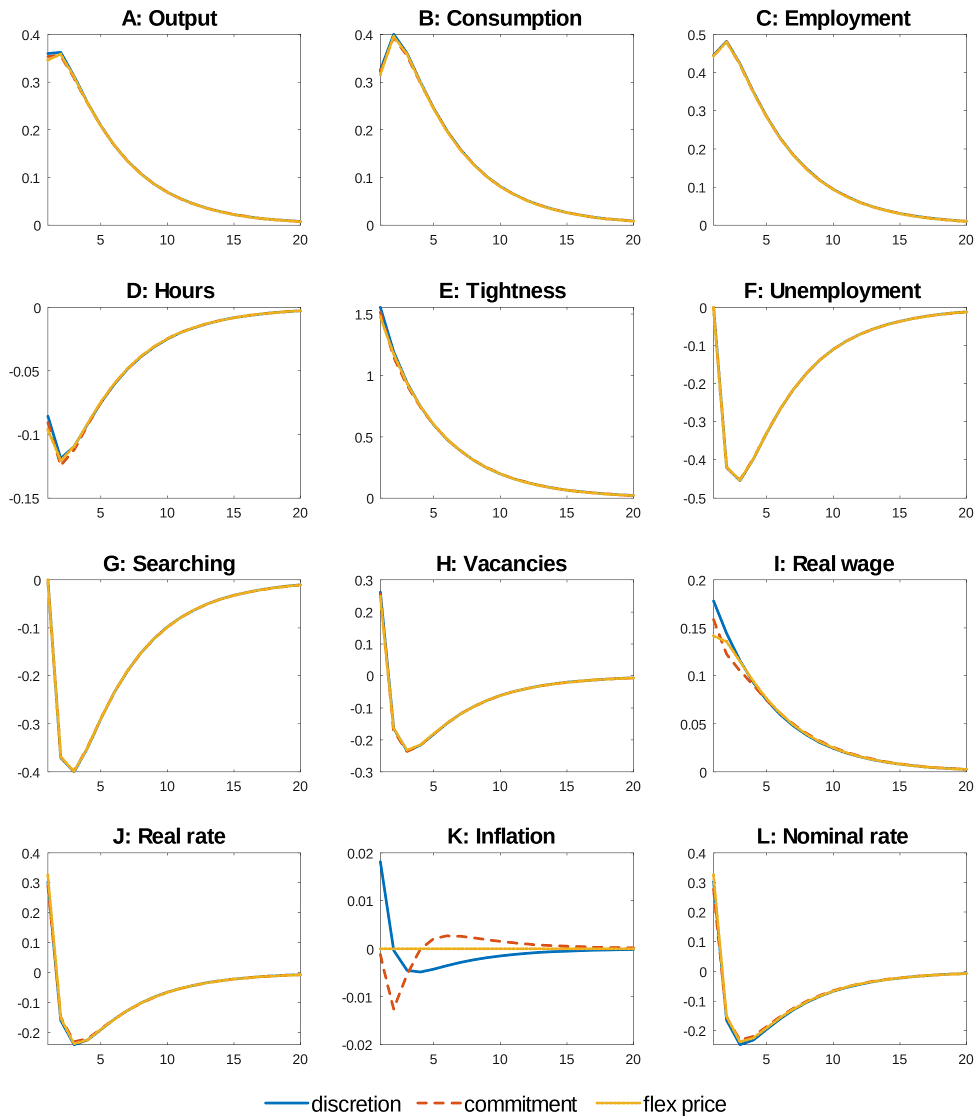

Fig. 2: Impulse responses to a positive 1 s.d. matching efficiency shock.

5.2 Matching efficiency shock

The matching efficiency shock operates as an aggregate shock to the technology that produces matches between firms and the unemployed. Accordingly, an improvement in matching efficiency leads to more new jobs being created and hence to higher employment (panel C) from the existing levels of vacancies and unemployment. With the labor force fixed in size, higher employment translates into lower unemployment (panel F) and into greater labor market tightness (panel E), which, in turn, pushes up the real wage (panel I).

The improvement in matching efficiency raises the expected return to posting a vacancy leads to firms posting more vacancies (panel H), and makes it easier for firms to gain the labor services they need by substituting away from hours-worked-per-employee and toward having more employees. Thus, the rise in employment occurs alongside a decline in hours worked (panel D). Although hours-worked-per-worker declines, total (or aggregate) hours worked rises, which with the real wage increasing, leads to higher household income. The rise in household income is reflected in greater goods production (panel A) and in greater consumption (panel B). Interestingly, the real interest rate rises immediately following the shock (panel J) as households try to raise current consumption further by borrowing against future income. The households efforts to sell bonds in order to raise consumption further causes the real interest rate to rise and produces a rising consumption profile (panel B). As time passes and the effects of the improved matching efficiency begin to wain, households' desire to save current income in order to finance future consumption asserts itself, causing the real interest rate to decline and for consumption to following a decreasing profile. The result is that consumption exhibits a hump-shaped pattern in response to the shock.

As previously, the responses are not especially sensitive to how monetary policy is conducted: both commitment and discretion are able to closely replicate the behavior of the flex-price equilibrium. However, some difference between commitment and discretion can be seen in the behavior of inflation. (panel K), although the magnitude of the inflation response is small. Where inflation initially falls and then rises above its mean when policy is conducted with commitment it initially rises and then falls below its mean when policy is conducted under discretion. The differences in inflation's behavior are largely driven by real marginal costs and the real wage. Under discretionary monetary policy, the real wage rises by more in response to the shock than under commitment, which flows through to higher real marginal costs and higher inflation.

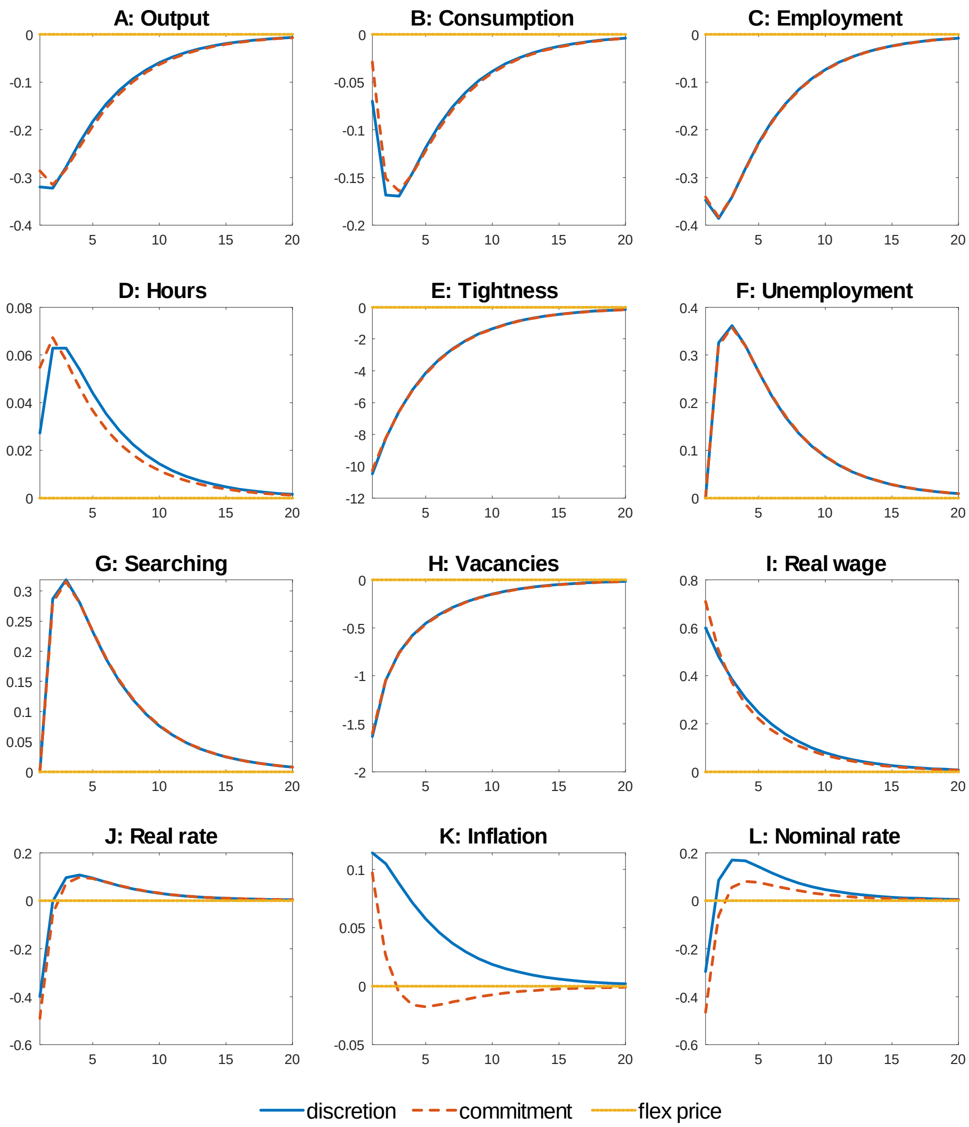

Fig. 3: Impulse responses to a positive 1 s.d. bargaining power shock.

5.3 Bargaining power shock

An increase in worker bargaining power shifts some of the match-surplus away from firms and towards workers, allowing workers to garner a greater proportion of the surplus. With greater bargaining power, workers obtain higher real wages (panel I) and increase their hours worked (panel D) while, as a consequence of receiving a smaller share of the match-surplus, firms post fewer vacancies (panel H) and hire fewer workers, leading to a decline in employment (panel C).

The positive shock to worker bargaining power leads to a decline in labor market tightness (panel E) as vacancies fall and unemployment rises (panel F). Although there is a small increase in hours worked and the real wage rises, the decline in employment is sufficiently large as to lower household income, goods production (panel A) and aggregate consumption (panel B). Driven by the aggregate employment dynamics, household consumption follows a decreasing profile over the short-run, during which households efforts to smooth consumption serve to lower the real interest rate (panel J). With inflation rising in response to the shock, monetary policy responds by raising the nominal interest rate (panel L), however the extent of the policy tightening is muted by the decline in the real interest rate.

Although outcomes under commitment and discretion are close to the flex-price outcomes for most of the key macroeconomic variables, notable differences can be seen in how inflation, the nominal interest rate, the real wage, and hours worked behave. The ability to commit, which leads to a smaller inflation response on impact and ensures inflation returns to zero relatively quickly (albeit with the standard overshoot associated with keeping the price level stationary), is absent under discretion. As a consequence, with discretionary policy inflation rises by more immediately following the shock and it remains elevated for a more sustained period. The behavior of inflation is reflected in the nominal interest rate, which is systematically tighter under discretion than under commitment.

5.4 Consumption preference shock

The consumption preference shock is the only shock in the model that acts somewhat like a demand shock. A one standard deviation increase in the consumption preference shock raises the utility obtained from consumption and increases the demand for consumption good, lifting consumption (panel B). To take advantage of the temporarily higher marginal utility of consumption, households are happy to work longer hours (panel D) even if the increase in hours worked comes at the cost of a slightly lower hourly real wage (panel I).

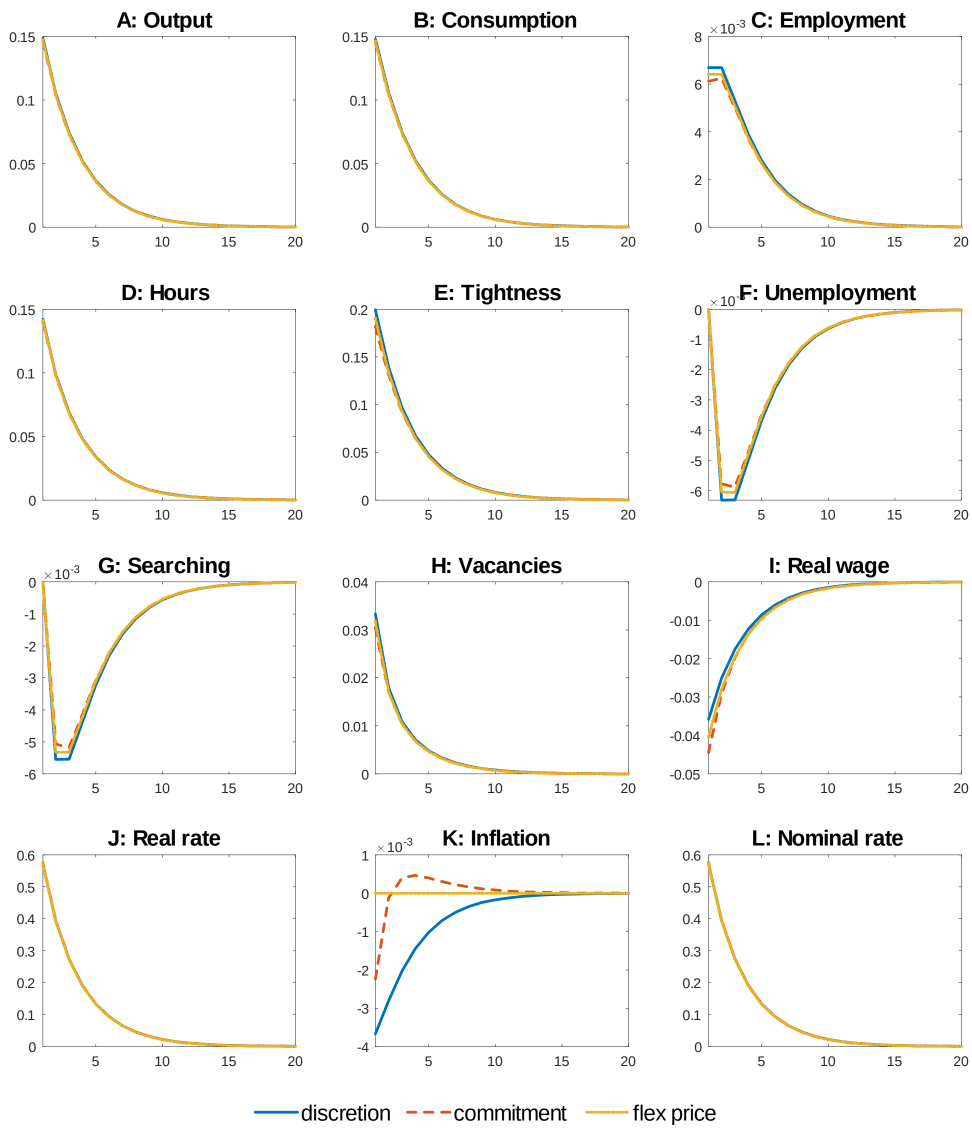

Fig. 4: Impulse responses to a positive 1 s.d. consumption preference shock.

In response to the higher demand for goods, firms post more vacancies (panel H) and hire more workers (panel C). Higher employment flows through to a decline in the unemployment rate (panel F) and to an increase in labor market tightness (panel E). Most of the labor market response comes in the form of higher hours worked, rather than higher employment, and the increase in the hours households are willing to work in order to raise their consumption serves to lower slightly the hourly real wage.

With households wanting to increase current consumption, their desire to borrow against future income to do so pushes up the real interest rate (panel J). Inflation declines (panel K), as the lower real wage reduces firms' real marginal costs. Although the consumption preference shock leads to a decline in inflation, the increase in the real interest rate more that offsets this decline and the nominal interest rate rises (panel L). Both commitment policy and discretionary policy are able to cope well with the shock, which has relatively little impact on inflation, and the behavior of the real economy replicates closely that of the flex-price equilibrium.

5.5 Elasticity of substitution shock

The shock to the elasticity of substitution behaves similarly to the markup shock often present in linearized models. An increase in the elasticity of substitution among goods reduces firms' monopolistic power, which raises output (panel A), household income, and consumption (panel B).

The decline in market power that occurs when goods become closer substitutes leads to a decline in the price markup over real marginal costs and to an increase in production. In order to raise production firms require more labor, thus hours worked increase (panel D), and firms post more vacancies (panel H) and raise employment (panel C). With employment increasing, unemployment decreases, which, with the rise in posted-vacancies, leads to an increase in labor market tightness (panel E) and to a rise in the hourly real wage (panel I). As expected, then, the decline in monopolistic power leads to labor receiving a greater share of output, with this increase driven by a rise in hours worked and a rise in the real wage.

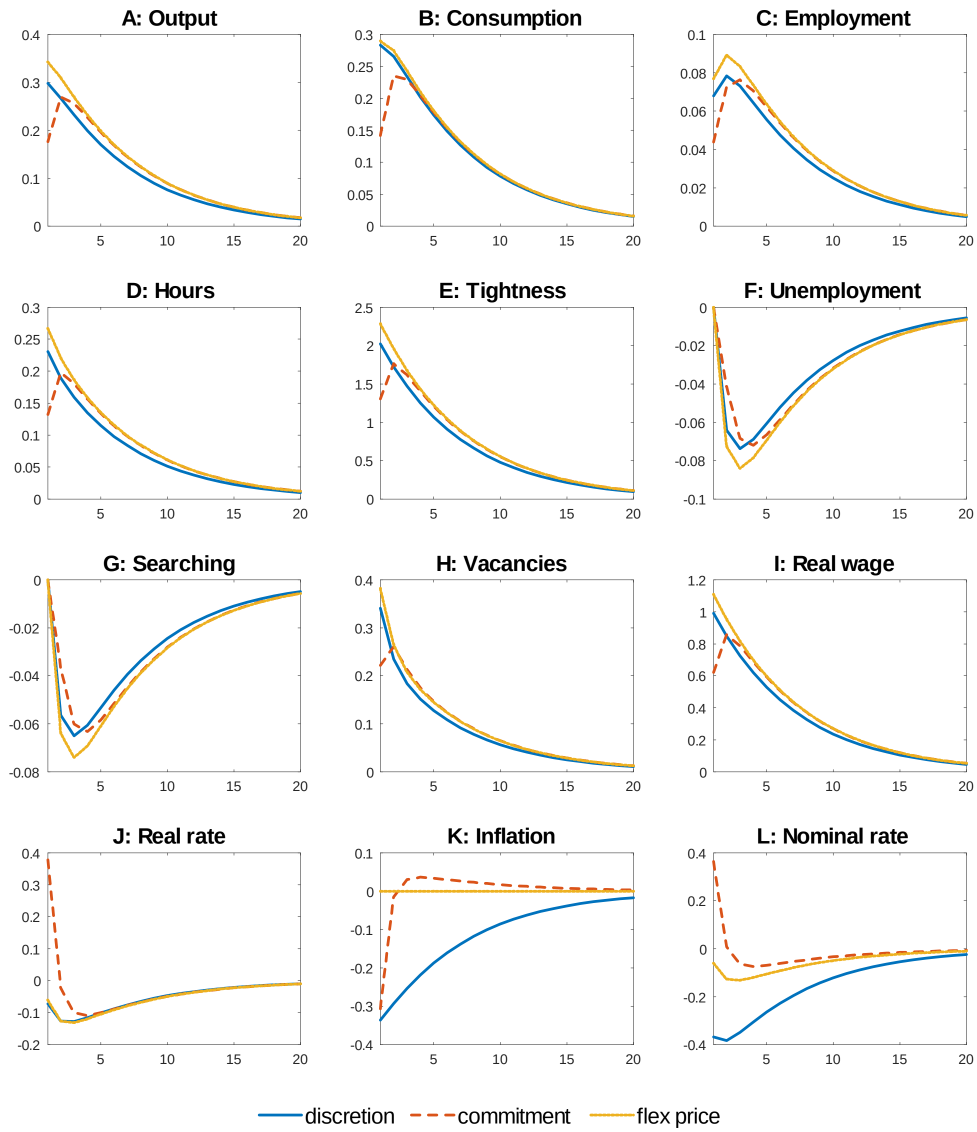

Fig. 5: Impulse responses to a positive 1 s.d. elasticity of substitution shock.

The increase in the real wage pushes up real marginal costs, which exerts upward pressure on inflation, however the price markup falls and on balance inflationary pressures ease and inflation falls (panel K). The increase in consumption generated by the temporary boost in income causes the real interest rate to rise (panel J). Looking at the nominal interest rate, whether monetary policy tightens or loosens in response to the shock depends on how monetary policy is conducted. When monetary policy is conducted under discretion, the decline in inflation caused by the shock is both larger and more persistent than under commitment and the result is that monetary policy is loosened and the nominal interest rate in lowered. For commitment policy, although inflation declines when the shock occurs, the central bank's commitment to price stability causes inflation to return quickly to its mean, with a small overshoot occurring in order to keep the price level stationary.

6 Outcomes for simple rules

The previous section focused on optimal monetary policy, assuming that the central bank conducted policy under either commitment or discretion. There we showed that, although there were some differences, both discretion and commitment generally came close to replicating the dynamic behavior of the flex-price equilibrium. In this section we assume that the central bank does not conduct policy optimally, but commits to simple rules instead. We consider two simple targeting rules and Strict Inflation Targeting (SIT), all three of which feature prominently in the literature.

$$1 + R_t = \frac{1+\overline{\pi}}{\beta}\left(\frac{1+\pi_t}{1+\overline{\pi}}\right)^{\phi_\pi}\left(\frac{Y_t}{Y_{t-1}}\right)^{\phi_y}, \tag{61}$$

$$1 + R_t = \frac{1+\overline{\pi}}{\beta}\left(\frac{1+\pi_t}{1+\overline{\pi}}\right)^{\phi_\pi}(1+u_t-\overline{u})^{\phi_u}, \tag{62}$$

$$\pi_t = \overline{\pi}. \tag{63}$$

Equation (61) is a form of Taylor-type rule, but where monetary policy responds to output growth rather than to the output gap (An and Schorfheide, 2007). This rule is in the spirit of a "speed limit" policy (Walsh, 2003) in which the interest rate is raised when output is growing rapidly. It's dependence on output growth means that it does not require keeping track of flex-price output. We parameterize this rule by setting $\phi_\pi = 2.5$, and $\phi_y = 0.5/4$. Equation (62) is also a form of Taylor-type rule, but in this case it is the unemployment rate rather than the output gap that monetary policy responds to (Orphanides and Williams, 2002). We parameterize this rule by setting $\phi_\pi = 2.5$, and $\phi_u = 1.5/4$. Lastly, equation (63) characterizes strict inflation targeting whereby the central bank conducts monetary policy to keep inflation outcomes equal to the inflation target period-by-period (Svensson, 1999, 2002). In all three simple rules we set $\overline{\pi}$ so that annualized quarterly inflation equals 1.8 percent, ensuring that that average inflation for each of the simple rules is comparable to that for discretion.

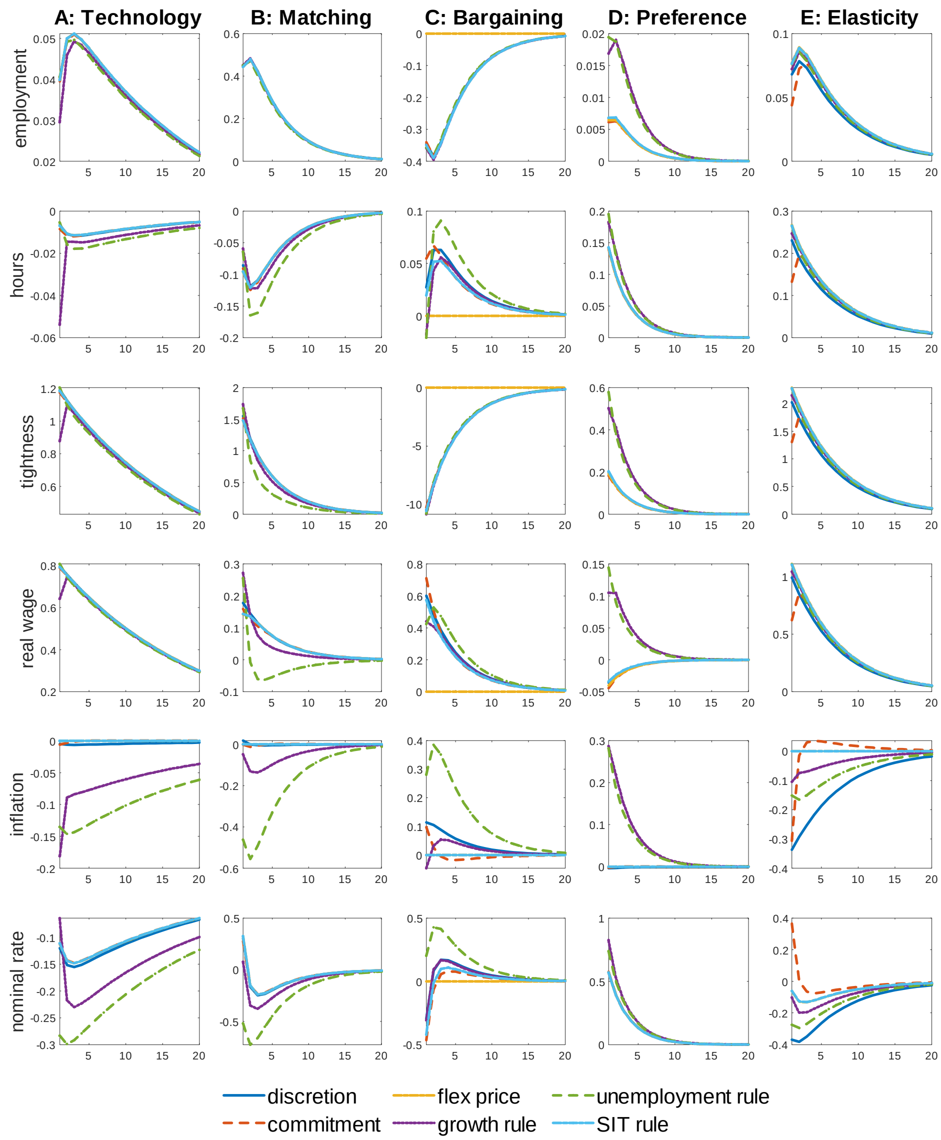

Fig. 6: Impulse responses for different policy rules.

Solving the model and computing the impulse responses for each of these simple policy rules, Figure 6 displays the resulting responses alongside those for commitment, discretion, and the flex-price economy for all five shocks, focusing on the variables where differences across policies are most evident.

Figure 6 reveals several general findings. First, because it keeps inflation stable, the strict inflation targeting rule generally behaves similarly to commitment and discretion, which in turn are very similar to the flex-price economy. This suggests that strict inflation targeting is likely to perform well from a welfare perspective. Second, the output growth Taylor-type rule and the unemployment rate Taylor-type rule differ greatly from commitment and discretion in regard to inflation and the nominal interest rate for all shocks other than the price elasticity shock. These differences are largely quantitative in nature and suggest that inflation and nominal interest rates are much more volatile under either of these Taylor-type policies. Third, the Taylor-type rule that responds to the unemployment rate generally results in inflation moving more in response to a shock's impact, and has the economy returning more slowly to baseline. This behavior is most evident in the responses to shocks to technology, the matching efficiency, and bargaining power. Fourth, although the inefficiencies of the simple rules are clearly present in the behavior of the nominal variables, they can also be seen in labor market outcomes, mostly notably in hours worked and the real wage, and most clearly for shocks to the matching efficiency and bargaining power. Clearly, these shocks have greater impact on the labor market and the real economy when policy is conducted according to either one of the simple Taylor-type rules.

Before concluding this section, we report in Table 3 average inflation and the unconditional probability with which the nominal interest rate is negative, where these statistics are computed by simulating one million observations from each model. Although we do not impose the Zero Lower Bound (ZLB) when solving the model, we report these statistics to gauge the extent to which not imposing the ZLB may be important.

Table 3. Average Inflation and the Zero Lower Bound

Rule	Average Inflation	ZLB probability
Commitment	0.00043	0.00077
Discretion	1.81702	0.00001
Taylor rule: growth	1.78916	0.00015
Taylor rule: unemployment	1.81058	0.00296
Strict inflation targeting	1.80000	0.00000
Flex-price	0.00000	0.00054

Table 3 shows that the probability of encountering the ZLB is small—considerably less than half of one percent—for all policies considered. The flex-price economy has a higher probability of encountering the ZLB than strict inflation targeting because the latter assumes an inflation target of 1.8 percent while for the former average inflation is zero. For a similar reason, the positive average inflation generated by the discretionary inflation bias leads to the ZLB being encountered less frequently under discretion than commitment. With comparable outcomes for average inflation, the two Taylor-type rules (especially the rule that responds to the unemployment rate) are more likely to encounter the ZLB than discretion, but these probabilities are still very small. The results in Table 3 suggest that for the shocks we are considering, violations of the ZLB are extremely unlikely events.

7 Conclusion

In this paper we have developed and analyzed a nonlinear DSGE model characterized by monopolistic competition and price-rigidity in the goods market and job-matching in the labor market. The model allows for shocks to the matching efficiency and worker bargaining power, and to technology, the elasticity of substitution between goods, and the household's preference for consumption goods. The former two shocks have not been analyzed widely in the literature, but are included in order to better understand the role these shocks might have played during the Great Recession. We consider a host of different monetary policy regimes/rules and compare the economic outcomes they produce to those for the flex-price equilibrium.

Two of the policy regimes we consider have monetary policy conducted optimally. The first assumes that the central bank can commit while the second assumes policy is conducted under discretion. Although these two policies differ in terms of the average inflation outcome, with discretion leading to an inflation bias of about 1.8 percent per year, they produce very similar impulse responses, indicating little evidence that discretionary stabilization bias is important. In addition, other than for inflation and the nominal interest rate, the impulses responses for commitment and discretion behave very similarly to those for the flex-price equilibrium. This finding suggests that for the real economy the shocks we consider, which include those to the matching efficiency shocks and bargaining shocks, do not pose a problem for a central bank that conducts monetary policy optimally.

We also consider strict inflation targeting and two regimes in which monetary policy is conducted according to a Taylor-type rule: one where policy responds to inflation and real output growth and the other where policy responds to inflation and the unemployment rate. Analyzing the impulse responses for these three policy rules we find that strict inflation targeting behaves similarly to commitment and discretion and hence also to the flex-price equilibrium.

However, the same cannot be said for the two Taylor-type rules, but of which generated behavior that differed greatly from the flex-price equilibrium. Pursuing either of these Taylor-type rules made inflation and the nominal interest rate more volatile and more persistent and also led to inefficient labor market outcomes, especially in response to shocks to the matching efficiency and workers' bargaining power. This finding suggests that the inability to conduct monetary policy optimally can allow these shocks to have an impact of the labor market that is both large and inefficient.

A Appendix - Model solution

In this appendix we summarize the method used to solve the model. We use a nonlinear solution method because our discretionary policy problem cannot be formulated as a linear-quadratic problem (because the flex-price equilibrium is not efficient). With five shocks in the model and lagged employment as an endogenous state variable, there are six state variables in the flex-price model and in the discretionary policy model. In the case where the central bank can commit, we compute the commitment equilibrium which relies on two additional Lagrange multipliers as state variables, bringing the total number of state variables for this case to eight. Expectations are computed using Gauss-Hermite quadrature, with 5 nodes for each of the five shocks. All unknown functional forms are approximated using Smolyak's sparse grid (Smolyak, 1963) with Chebyshev polynomials used to form the basis functions. For the Smolyak approximation we used 4 layers, leading to a grid containing 1457 nodes for the six-state specifications, 2465 nodes for the seven-state specification, and 3937 nodes for the eight-state specification. Our implementation follows Judd, Maliar, Maliar, and Valero (2014). For each specification, the deterministic steady state (layer equal to 0) was used as the initial conjecture of the solution, with the final solution arrived at by adding successive layers to the grid via a form of homotopy. The impulse response functions are computed following Potter (2000), with Monte Carlo integration (10,000 replications) employed to integrate out the initial state and the future innovations.

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