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Efficiency Wage and Cyclical Asymmetry*

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Abstract This paper examines the cyclical implications of the efficiency wage model for the labor market and inflation dynamics in a New Keynesian framework with search frictions. Shapiro and Stiglitz's (1984) efficiency wage framework is incorporated into the otherwise ordinary Nash-bargaining wage determination, thereby generating downward real wage rigidity over business cycles. Introducing the efficiency wage scheme enables the model to replicate the asymmetric dynamics of real activity indicators, especially labor market quantities, observed in the data; the model exhibits a significantly left-skewed distribution for employment, vacancy, and real output. Furthermore, real wage rigidity induced by the efficiency wage scheme can address Shimer's (2005) volatility puzzle and explain the observed weak cyclicality of real wages.

Keywords efficiency wage, downward real wage rigidity, cyclical asymmetry, volatility puzzle

JEL Classification E24, E32, J64

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1. INTRODUCTION

Researchers have shown that the asymmetries in aggregate variables over the business cycle appear to be a key structural feature of the economy in many countries (e.g., Neftci, 1984; Sichel, 1993; McKay and Reis, 2008; Abbritti and Fahr, 2013). For example, in the United States, the growth rates of employment and vacancy are strongly left (negatively) skewed, hence occasionally falling sharply and usually growing in a steady manner. Contrarily, those of prices (measured by the GDP deflator) and real wages are highly right (positively) skewed. This right skewness implies sharp rises on rare occasions and downward rigidity of price adjustment. Studying what kinds of forces cause the asymmetries in the variables is important for deeply understanding the phenomena of recovery from the recession and fall from the boom over the business cycles, but this has been understudied.[1]

This paper studies the cyclical implications of real wage rigidity for the asymmetries in labor market and inflation dynamics under a New Keynesian framework combined with the Mortensen and Pissarides' (1994) labor market frictions. Specifically, we develop a variant of the New Keynesian model with labor search frictions by incorporating the real wage rigidity based on the efficiency wage framework of Shapiro and Stiglitz (1984). As in the recent New Keynesian literature, the model economy is characterized by monopolistic competition and price rigidity, plus the frictional labor market. A new feature is that Shapiro and Stiglitz's efficiency wage framework is incorporated into the otherwise ordinary Nash bargaining wage determination featured in the standard labor matching model. Since firms have imperfect information about a worker's effort, they must pay wages satisfying the so-called no-shirking condition, which places a lower bound on the worker's match surplus (downward real wage rigidity). The consequent downwardness of wage rigidity may well explain the cyclical asymmetry in labor market and inflation dynamics; in recessions, the downward rigidity forces firms to pay workers a relatively larger share of match surpluses, making profits more procyclical than in booms. Thus, negative shocks are absorbed mainly through a stronger decline in vacancy postings and employment, rather than through wage and price adjustment. Contrarily, in booms real wages and prices increase more flexibly, thereby limiting the hike in vacancy and employment. Furthermore, by dampening real wage fluctuations, this rigidity can possibly amplify fluctuations in vacancy postings and hiring as argued by Hall

[1] Abbritti and Fahr (2013) argue that the asymmetry explains the differing transmission of positive and negative monetary policy shocks from wages to inflation.

(2005) and Shimer (2005).

Key economic results of the model are summarized as follows. First, downward wage rigidity induced by the efficiency wage scheme can generate the observed asymmetric dynamics of real activity indicators and inflation; the efficiency wage model exhibits a significantly left-skewed distribution for employment, vacancy, and real output, but a right-skewed distribution for inflation along the business cycles. Moreover, when we impose a stricter limit on downward wage adjustment, i.e., fixing the efficiency wage level,[2] the fixed efficiency wage model remarkably amplifies the magnitude of skewness, even beyond the level observed in the data. This indicates that the real-world labor market lies at some mid-point between the baseline efficiency wage model and the fixed efficiency wage model. Consequently, the model can resolve the counterfactual symmetry commonly observed in the standard business cycle model.

Second, introducing real wage rigidity significantly amplifies the volatilities of labor market quantities and dampens real wage fluctuations. The fixed efficiency wage model generates even a higher magnitude of amplification in employment and vacancies, which is comparable to that observed in the data, and its dampening effect on real wage becomes more striking. Thus, the efficiency wage model can address the volatility puzzle[3] in the standard labor matching model and explain the observed weak cyclicality of real wages.

This paper's contributions to previous literature are three-fold. The first and second are empirical, and the last one is theoretical. First, relative to previous related studies, our model can explain better the observed asymmetric dynamics in main macroeconomic variables. McKay and Reis (2008) document asymmetric movement in employment; contractions are shorter and more violent than expansions. To explain this, McKay and Reis introduce a non-linear gain and cost function in technology adoption and asymmetric labor adjustment costs into a standard real business cycle model. Kim and Ruge-Murcia (2009) incorporate downward nominal wage rigidity into a standard New Keynesian model, and by estimating the model they find evidence supporting the downward nominal wage rigidity. However, they mainly aim to measure how much inflation is necessary to "grease the wheels" of labor markets under downward nominal wage rigidity,

[2]Beyond expositional purpose, constructing this artificial economy can be justified by the conjecture that in reality there may exist some institutional and economic factors that hinder the flexible adjustment of the efficiency wage level, such as legal minimum wage, social norm (see Hall (2005)), or implicit contracts between firms and workers (see Boldrin and Horvath (1995)).

[3]Shimer (2005) argues that the standard equilibrium search model of unemployment explains much less than 10% of the observed volatility in the U.S. data, given reasonable model specification and parameter values.

so they do not explore the implications of their model on cyclical asymmetry observed in main economic variables. Abbritti and Fahr (2013) try to explain the observed asymmetry by introducing asymmetric nominal wage adjustment costs, similar to the framework of Kim and Ruge-Murcia (2009). When they embed the asymmetric adjustment cost into a New Keynesian model with search frictions, they find that the presence of downward nominal wage rigidity strongly improves the fit of the model; it exhibits negative skewness for main labor market quantities and positive skewness for wage or price inflation. However, as indicated by earlier studies such as Dunlop (1938) and Tarshis (1939), nominal wage rigidities invoke counterfactual counter-cyclicality in real wage fluctuations upon demand shocks; among the above-mentioned studies, those introducing downward nominal wage rigidity are subject to the same old problem.

Second, our model matches the data well also in terms of the volatility in labor market quantities. As for the volatility puzzle, Shimer (2005) argues that a principal reason for this lack of amplification in labor market quantities over the business cycles is that the wage, set as an outcome of Nash bargaining, responds so procyclically that it offsets almost all of the effects of productivity shocks. As a natural response, a number of studies have attempted to offer a solution to the volatility puzzle by introducing wage rigidity. For example, Hall (2005) shows that a fixed wage, justified by the social norm functioning as a focal point for the possible outcomes of wage bargaining, can generate volatile fluctuations in unemployment and vacancies of an order of magnitude comparable to that in the data. Gertler and Trigari (2009) and Hall and Milgrom (2008) also introduce wage rigidity (from a staggered wage setting or as the outcome of a strategic bargaining game) and find that the introduced rigidity can substantially amplify fluctuations in unemployment and vacancies. Costain and Reiter (2008) argue that sticky wages seem to be a potentially promising way of improving the model's fit, particularly in terms of the relative volatility of unemployment to output. However, most of those studies are characterized as 'symmetric' wage rigidities, so that their models cannot reflect the observed downward rigidity in wage adjustment as documented in many previous empirical studies (e.g., Dickens et al., 2007; Holden and Wulfsberg, 2009).

Last but not least, by incorporating moral hazard into an otherwise standard flexible wage model, we provide a rich micro-foundation for endogenous downward wage rigidity. Most of the afore-mentioned studies are based on either exogenously fixed wage or an ad hoc form of wage functions,[4] thus they are

[4]For example, in many studies wage rigidities are embedded in a Calvo (1983) or Taylor (1980) type staggered manner (e.g., Gertler and Trigari, 2009) or as an ad hoc function of wage adjust-

lacking any relevant micro-foundation. In this regard, the paper closest to ours is Costain and Jansen (2010). Similar to our paper, by embedding Shapiro and Stiglitz's shirking model into the standard equilibrium search model, they introduce endogenous wage rigidity. While they mainly focus on explaining the volatility puzzle, which they failed to do, we emphasize the implications of endogenous downward wage rigidity in explaining the cyclical asymmetry.

The remainder of the paper is organized as follows. To motivate the analysis, Section 2 presents some stylized business cycle facts, paying special attention to the asymmetry and volatility of labor market variables and inflation. Section 3 develops the model. Section 4 describes the calibration of the model and reports the main findings. Section 5 concludes.

2. SOME STYLIZED FACTS ABOUT BUSINESS CYCLE DYNAMICS

To document some stylized facts about business cycles and compare them with model moments, we use real data from 1964Q1 2011Q4 obtained from various sources. The employment series (n) is total private employment from the Current Employment Survey (CES). For a fair comparison, the unemployment rate (u) is measured as the ratio of non-employment to the population over 16, since there exists no out-of-labor-force in the model. Vacancy (v) is measured by the Help-Wanted Advertising index compiled by the Conference Board. The inflation series (π) is quarterly growth rates of the GDP deflator (seasonally adjusted). The nominal interest rate (r) is measured by the effective federal funds rate. Real wages (w) are measured by (total private) average weekly earnings from the CES divided by the GDP deflator. The output series (y) is annualized real GDP in chained 2005 dollars compiled by the Bureau of Economic Analysis (BEA). The consumption series (c) is real private consumption expenditure from the BEA

Table 1 summarizes some selected moments of major macroeconomic variables in the U.S.[5] In the context of the motivation of this paper, two things are

ment cost (e.g., Kim and Ruge-Murcia, 2009; Abbritti and Fahr, 2013). Sometimes, wages are perfectly fixed at a constant level, justified by the social norm (see Hall (2005)) or the outcome of strategic bargaining games (see Hall and Milgrom (2008)).

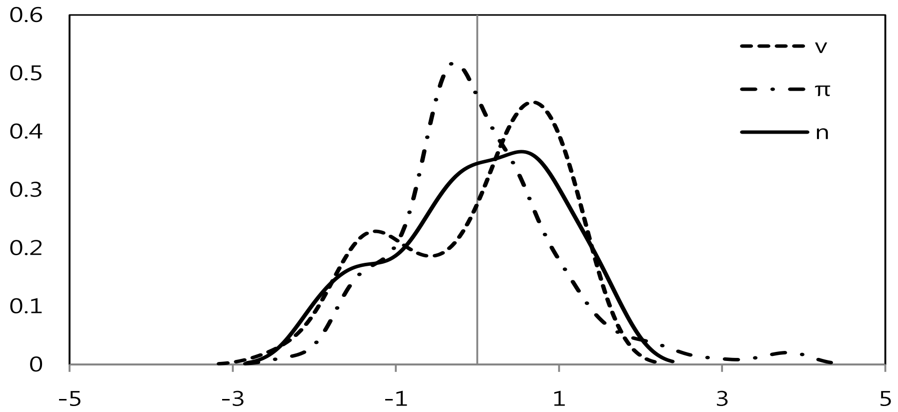
[5] In his seminal paper, Shimer (2005) detrended all the labor-market variables using an HP filter with smoothing parameter 10^5, the level of which is much higher than a conventional level. For a fair comparison and consistency, we detrend our data using an HP filter with the same value of smoothing parameter. When we apply the conventional level of smoothing parameter ($\lambda = 1600$ for quarterly data), there is no qualitative change in Table 1's results, except that the magnitude of

Table 1: Data moments

U.S. data (Quarterly)	Data moments				
	Standard Deviation (%)	Relative SD to y	Correlation with y	Autocorrelation	Skewness
n	2.4	0.969	0.832	0.968	-0.325
u	2.9	1.172	-0.819	0.972	0.202
$v/u(=\theta)$	21.2	8.505	0.772	0.955	-0.507
v	18.8	7.557	0.745	0.952	-0.534
π	0.4	0.144	0.188	0.659	0.970
r	0.5	0.218	0.216	0.899	0.954
w	1.7	0.674	0.554	0.960	0.567
y	2.5	1.000	1.000	0.941	-0.536
c	2.4	0.959	0.910	0.959	-0.428

Note: The sample period for the data is 1964Q1-2011Q4. All data series are reported as deviations from an HP(Hodrick-Prescott) trend with smoothing parameter 10^5. For details on the data, see Section 2.

Figure 1: Kernel density estimates for employment, vacancy, and inflation



Note: The sample period for the data is 1964Q1-2011Q4. For proper scaling, all the series are standardized before estimating kernel density. Thus, the measurement unit on the x-axis is one standard deviation of each corresponding variable.

worth noting: higher volatilities of labor market quantities relative to output and prominent asymmetries in labor quantities and inflation.

First, employment and vacancy posting are highly procyclical, and the volatility of employment is almost comparable to that of output; the relative volatility is close to unity. Moreover, vacancy posting is much more volatile than output. Shimer (2005) focused on the standard equilibrium search model's inability to explain this striking volatility of employment and vacancy. Contrarily, real wage is only weakly procyclical, and its volatility is much lower than that of output, as is well documented in previous empirical studies. These observations motivate us to introduce real wage rigidity as an additional amplifying mechanism, as suggested by Hall (2005) and Gertler and Trigari (2009).

Second, as documented in Abbritti and Fahr (2013),[6] the asymmetries in the main macroeconomic variables over the business cycle appear to be a key structural feature of the U.S. economy; employment and vacancy posting are strongly negatively skewed, hence occasionally falling sharply and usually growing in a steady manner. Contrarily, the inflation rate of the GDP deflator is highly posi-

volatilities in most variables is uniformly reduced.

[6]Many other studies have documented similar cyclical asymmetry; for example, see Neftci (1984), Sichel (1993), McKay and Reis (2008), and Barnichon (2012).

tively skewed. This positive skewness implies sharp rises on rare occasions and downward rigidity of price adjustment. Positive skewness is also the case for real wages, though its magnitude is much smaller.

To effectively visualize the cyclical distribution of the main variables, Figure 1 plots the kernel density estimates of employment (n), vacancy (v), and inflation (π) using a Gaussian kernel with optimal bandwidth. Consistent with Table 1, it exhibits a significantly left-skewed distribution for employment and vacancy but a highly right-skewed distribution for inflation with a long right tail. This observation motivates us to explore to what extent introducing downward wage rigidity can generate cyclical asymmetries similar to the ones observed in the data.

3. MODEL ECONOMY

3.1. THE ENVIRONMENT

There is a unit mass of identical households in the economy. Each member in a representative household can be either employed or unemployed. Firms in the production sector are monopolistically competitive, produce a differentiated good using labor as only input, and face a price adjustment cost à la Rotemberg (1982).

The labor market is characterized by a New Keynesian variant of Mortensen and Pissarides' (1994) matching model, and the Shapiro and Stiglitz's (1984) efficiency wage framework is incorporated into the otherwise ordinary Nash bargaining process. As we will show later, this implies that, given the realized productivity shocks, when the Nash bargaining wage is above a minimum efficiency wage level, firms may pay the bargain wage; otherwise, firms should pay the efficiency wage in order to maintain incentive compatibility so that workers will not shirk. In equilibrium, no workers actually shirk because the incentive compatibility condition always holds.

The timing of events in the model economy is as follows:

1. Aggregate productivity shocks are realized and known by every agent.
2. Firms post vacancies and new matches occur accordingly.
3. Exogenous separation (quitting) or the firing of (detected) shirking workers occurs.
4. Firms and workers bargain with each other over contingent real wages.
5. Firms set the price of their products
6. Production takes place; that is, workers determine whether to shirk or not, and

idiosyncratic productivity shocks are realized.
7. Produced consumer goods and government bonds are traded in the product and asset market, respectively.

Note that the realized idiosyncratic shocks are unverifiable between firms and workers; firms only observe ex post total output, conditional on known aggregate productivity and technology.[7] Thus, there is no ex ante heterogeneity; every worker is treated equally in the bargaining and production process. We also assume that the level of unobserved effort and the idiosyncratic shocks are unverifiable by a third party, so the worker-firm relationship must be sustained by a bilateral incentive-compatible contract instead of by a contract enforceable by any third party, e.g., the court.

In addition to the assumption of unobservable effort, this ex ante homogeneity is essential in order to make workers' threat to shirk credible. For example, if both aggregate and idiosyncratic productivities are verifiable, given a firm's technology, firms can infer the level of effort that workers have exerted so that firms can punish any shirking worker. While in Shapiro and Stiglitz (1984) the information asymmetry is directly "assumed," here it is derived from the firm's lack of information about idiosyncratic productivity.

Another important implication of this ex ante homogeneity is that endogenous separation can be justifiably ruled out in the model. Since a production decision is based only on the ex ante "expected" surplus, as long as both the firm's expected net surplus and the worker's expected utilities are positive, the match is maintained. Thus, even if endogenous separation is allowed, it does not occur at all in any non-trivial equilibrium of the model. This absence of endogenous separation is one of the main differences from Costain and Jansen (2010).

3.2. HOUSEHOLD

A representative household is made up of a continuum of members with a unit mass. As in Merz (1995) and Andolfatto (1996), household members fully pool their income and consumption. Under the assumption of perfect insurance, consumption is equalized across household members at a given period. This is equivalent to assuming the existence of one large household, of which each member intratemporally acts like a risk-neutral agent.

[7] In contrast to firms, observing their own effort level, workers can infer the realized idiosyncratic shock in an ex post manner.

The representative household maximizes its expected lifetime utility,

$$E_0[\sum_{t=0}^{\infty}\beta^t(\frac{c_t^{1-\sigma}}{1-\sigma}-n_t e_t)] \tag{1}$$

subject to the sequence of the real budget constraint,

$$c_t+\frac{b_t}{p_t}=\bar{w}_t n_t+w^u(1-n_t)+\frac{\Theta_t}{p_t}-\frac{\tau_t}{p_t}+R_{t-1}\frac{b_{t-1}}{p_t} \tag{2}$$

Here, e_t is the disutility from a worker's effort, b_t is a one-period nominal bond, $\bar{w}_t$ is an expected wage, n_t is a fraction of working household members, w^u is the value from non-market activity, Θ_t is the dividend from the profits of household-owned firms, τ_t is a lump-sum tax and R_t is the gross nominal interest rate. A worker may either choose to work, i.e., to incur the disutility $e_t = e^*\lambda_t > 0$ from his efforts, or to shirk $e_t = 0$, where e^* is the utility cost of efforts in consumption unit and $\lambda_t = c_t^{-\sigma}$ denotes the marginal utility of consumption.

Note that due to the presence of perfect income sharing, an individual's budget constraint does not depend on his employment history and current status. The intertemporal optimality condition yields the standard Euler equation.

$$c_t^{-\sigma}=\beta R_t E_t(\frac{c_{t+1}^{-\sigma}}{\pi_{t+1}}) \tag{3}$$

where $\pi_{t+1}=\frac{p_{t+1}}{p_t}$.

3.3. FIRMS

We assume a continuum of firms uniformly distributed and indexed by $i \in [0,1]$, each producing differentiated consumption goods. Each firm creates a continuum of jobs, uniformly distributed and indexed by $j \in [0,1]$, summing up to measure one and the jobs are either vacant or filled by workers. Each job in a firm has access to a constant-returns production technology. The technology of a representative filled job j in firm i is characterized by $y_{it}^j = a_t x_{it}^j n_{it}^j e_{it}^j$, where n_{it}^j is the number of workers hired by job j of firm i, and a_t is an aggregate productivity shock, while x_{it}^j is an i.i.d. idiosyncratic (job-specific) productivity shock. Each shock evolves according to:

$$\ln a_t=(1-\rho_a)\ln a+\rho_a\ln a_{t-1}+\varepsilon_t^a, \quad \varepsilon_t^a\sim N(0,\sigma_a^2)$$

$$\ln x_{it}^{j} \sim N(0, \sigma_x^2)$$

Note that if the worker chooses to shirk, $e_{it}^{j} = \underline{e} > 0$; otherwise, $e_{it}^{j} = \bar{e}$, where $0 < \underline{e} < \bar{e}$.[8] Here, we assume that $\underline{e}$ is so low that no firms would let workers shirk in any non-trivial equilibrium. Thus, to avoid a trivial equilibrium where workers choose to shirk ($e_{it}^{j} = \underline{e}$), firms are supposed to pay at least above a certain level of the efficiency wage. In the symmetric equilibrium across jobs, by the law of large numbers, the technology of each job j can be aggregated into the whole firm i's technology

$$y_{it} = a_t n_{it} e_{it} \bar{x}, \quad \bar{x} = \int_0^{\infty} x dF(x) \tag{4}$$

where $F(x)$ is a cumulative distribution function of idiosyncratic productivity shock x —note that here a time subscript is suppressed since it is an i.i.d. shock. Here, n_{it}, e_{it}, and y_{it} are firm i's total employment, inputted effort, and real output, respectively.[9]

Unemployed workers are matched with vacant jobs through constant returns to scale matching technology $M(u,v) = \zeta u^{\xi} v^{1-\xi}$. Thus, the number of employed workers at time t in each firm i evolves according to:

$$n_{it} = (1-\rho)(n_{it-1} + v_{it} q(\theta_t)) \tag{5}$$

where v_{it} is the number of vacancies opened by firm i, and $q(\theta_t)$ is the probability that an open vacancy is matched with a worker. Here,

$$\theta_t = \frac{v_t}{u_t}, \quad q(\theta_t) = \zeta \theta_t^{-\xi} \tag{6}$$

where v_t and u_t are total number of vacancies and the unemployed.

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[8] The reason why $\underline{e} > 0$ is as follows; if $\underline{e} = 0$, it implies that the job operated by a shirking worker produces nothing. This harms the plausibility of the information asymmetry assumption that a worker's effort cannot be observed by firms, which is an essential prerequisite for moral hazard.

[9] By symmetry across jobs, $n_{it}^{j} = n_{it}$ and $e_{it}^{j} = e_{it}$ for all j, then $n_{it} = \int_0^1 n_{it}^{j} dj$ and $e_{it} = \int_0^1 e_{it}^{j} dj$. By the law of large numbers, firm i's total output $y_{it} = \int_0^1 y_{it}^{j} dj$ is derived by $y_{it} = E(y_{it}^{j}) = \int_0^{\infty} a_t n_{it} e_{it} x dF(x) = a_t n_{it} e_{it} \bar{x}$.

Opening a new vacancy costs firms a unit cost κ. Open vacancies are matched with the total pool of searching workers, which is given by the total labor force minus the number of employed workers in the previous period, $u_t = 1 - n_{t-1}$. The representative firm chooses $\{p_{it}, n_{it}, v_{it}\}_{t=0}^{\infty}$ to maximize the expected profit in real terms,

$$Max\ E_0\{\sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0}[\frac{p_{it}}{p_t}y_{it} - \bar{w}_t n_{it} - \kappa v_{it} - \frac{\varphi}{2}(\frac{p_{it}}{p_{it-1}} - 1)^2]\}$$

subject to the demand for each variety of consumption goods $y_{it} = (\frac{p_{it}}{p_t})^{-\eta} y_t$, [10] where the parameter η denotes the elasticities of substitution among differentiated consumption goods, the firm's technology (equation (4)), and the law of motion of employment (equation (5)), taking as given the contingent wage schedule determined by the bargaining process, which will be described later. Here, the term $\frac{\varphi}{2}(\frac{p_{it}}{p_{it-1}} - 1)^2$ represents a price adjustment cost of Rotemberg (1982) type.

From the optimal conditions, the following equations are derived (the subscript i is dropped by symmetry);

$$\partial v_t : \mu_t = \frac{\kappa}{(1-\rho)q(\theta_t)} \tag{7}$$

$$\partial n_t : \frac{\kappa}{q(\theta_t)} = (1-\rho)(mc_t a_t \bar{x}_t \bar{e} - \bar{w}_t) + E_t[\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(1-\rho)\frac{\kappa}{q(\theta_{t+1})}] \tag{8}$$

$$\partial p_t : \varphi(\pi_t - 1)\pi_t = y_t(1 - \eta + \eta mc_t) + E_t[\beta\varphi(\frac{c_{t+1}}{c_t})^{-\sigma}(\pi_{t+1} - 1)\pi_{t+1}] \tag{9}$$

where real marginal cost mc_t is the Lagrange multiplier on the equilibrium condition for each variety of consumption goods, and the marginal value of a worker to firms μ_t is the Lagrange multiplier on constraint (5), and $\bar{w}_t$ is the expected value of contingent wage satisfying $\bar{w}_t = \int_0^{\infty} w_t(x)dF(x)$. Equation (9) represents a Rotemberg-type variant of the New Keynesian Phillips curve.

The labor demand condition (8) will characterize the labor market equilibrium, once it is combined with the wage function, which will be derived in the next section.

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[10] When the aggregate output in final consumption goods is defined by CES aggregator, such as $y_t = [\int_0^1 (y_{it})^{(\eta-1)/\eta} di]^{\eta/(\eta-1)}$, solving the cost minimization problem leads to the allocation of demands on each variety of differentiated consumption goods, $y_{it} = (\frac{p_{it}}{p_t})^{-\eta} y_t$, where $p_t \equiv [\int_0^1 (p_{it})^{1-\eta} di]^{1/(1-\eta)}$ is the aggregate price index.

3.4. WAGE BARGAINING

We consider a bilateral wage bargaining problem when firms face the incentive-compatibility constraint induced by workers' moral hazard. Since firms cannot perfectly observe or verify workers' effort level, the workers' threat to shirk is credible. Firms can detect a shirking worker only with a probability of $0 < d < 1$; once caught, the worker would be fired. To induce workers to exert effort, firms are supposed to pay at least the wage (the efficiency wage) that maintains the incentive compatibility (the no-shirking condition, NSC), which ensures that the workers' value of exerting effort exceeds the value of shirking. In sum, workers' wages are determined basically by a conventional Nash bargaining process, but this bargaining process is constrained by the incentive-compatibility consideration to avoid workers' shirking. As a result, the expected wage is characterized by the weighted average of two different wage schemes: the Nash bargaining wage and the efficiency wage.

Before going over the wage bargaining problem, we need to describe the contingent asset values for firms and workers. The asset value of non-shirking workers V_t^E is

$$V_t^E = w_t - e^* + E_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}[(1-\rho)max(V_{t+1}^E, V_{t+1}^S) + \rho V_{t+1}^U]\} \tag{10}$$

The asset value of workers who are shirking V_t^S is

$$V_t^S = w_t + E_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}[(1-\rho)(1-d)max(V_{t+1}^E, V_{t+1}^S) + ((1-\rho)d+\rho)V_{t+1}^U]\} \tag{11}$$

Note that in a non-trivial equilibrium, the NSC is always satisfied so that $max(V_t^E, V_t^S) = V_t^E$ holds for any t.

The asset value of the unemployed V_t^U is

$$V_t^U = w^u + E_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}[p(\theta_{t+1})(1-\rho)V_{t+1}^E + (1-p(\theta_{t+1})(1-\rho))V_{t+1}^U]\} \tag{12}$$

where $p(\theta_t)$ is the probability that workers find a job, $p(\theta_t) = \zeta\theta_t{}^{1-\xi}$. By using equations (10) and (11), the NSC is derived as

$$V_t^E \geq V_t^S \Leftrightarrow E_t[\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(1-\rho)(V_{t+1}^E - V_{t+1}^U)] \geq \frac{e^*}{d} \qquad \text{(NSC)} \tag{13}$$

On the firm's side, the asset value of a filled job V_t^J is (for simplicity, the scripts i and j will be suppressed from now on.)

$$V_t^J = mc_t a_t x_t \bar{e} - w_t + E_t[\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(\rho V_{t+1}^V + (1-\rho)V_{t+1}^J)] \tag{14}$$

Under the free-entry condition for job openings, the asset value of an unfilled vacancy V_t^V is zero, $V_t^V = 0$. Substituting this into (14) and aggregating over jobs, we can confirm that equation (14) becomes equivalent to the condition (8), and therefore the asset value of an operating job V_t^J is expressed as $V_t^J = \mu_t = \frac{\kappa}{(1-\rho)q(\theta_t)}$.

For later use, we rewrite the net value of non-shirking workers. Subtracting equation (12) from (10), we have

$$V_t^E - V_t^U = w_t - w^u - e^* + E_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(1-\rho)(1-p(\theta_{t+1}))(V_{t+1}^E - V_{t+1}^U)\} \tag{15}$$

With the value functions defined above, the wage bargaining problem that firms and workers face at every period can be expressed as follows:

$$Max_{w_t}(V_t^E - V_t^U)^b(V_t^J)^{1-b}, \quad \text{subject to} \quad V_t^E \geq V_t^S \tag{16}$$

where $b \in [0,1]$ measures the relative bargaining power of workers. By solving problem (16) with or without the binding constraint (NSC), we can derive each wage function for two different types of wage scheme: the efficiency wage and the Nash bargaining wage.

One thing to note is that to ensure that workers do not shirk, firms should commit themselves to guaranteeing a minimum wage level (the efficiency wage) for the next period, not for the current period. This is due to the forward-looking nature of the NSC of (13); the net surplus of the non-shirking worker relative to the shirking worker ($V_t^E - V_t^S$) depends on the net surplus of the non-shirking worker relative to the unemployed worker in the next period, ($V_{t+1}^E - V_{t+1}^U$). Thus, it is future wages that influence the worker's incentive to shirk now. Unless firms commit themselves to paying at least the efficiency wage in the next period, which corresponds to the minimum surplus level satisfying the NSC (13), workers have no incentive not to shirk in the current period.

Another related point is that at a given time period, the efficiency wage should play a dual role: fulfilling the minimum surplus that the firm committed to in the previous period and making another commitment for the surplus in the next period, so as to satisfy the NSC of the current period. As seen in (15), the net surplus of workers in the current period ($V_t^E - V_t^U$) depends on the expected net surplus of workers in the next period ($V_{t+1}^E - V_{t+1}^U$). Thus, given a minimum level of net surplus in the current period to which the firm committed in the previous period, for the current efficiency wage level to be uniquely determined, the net surplus of workers in the next period ($V_{t+1}^E - V_{t+1}^U$) should be simultaneously committed to the minimum level that satisfies the binding NSCs of both the previous and the current period. In this way, the efficiency wage level in the current period is simultaneously determined with the committed level of net surplus for the next period.

First, when the NSC is not binding in the current period, the equilibrium wage (the Nash bargaining wage) can be written as

$$w_t^{NB} = (1-b)(w^u + e^*) + bmc_t a_t x_t \bar{e}$$

$$+bE_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}[\frac{\kappa}{q(\theta_{t+1})} - \frac{1-b}{b}(1-\rho)(1-p(\theta_{t+1}))(V_{t+1}^E - V_{t+1}^U)]\} \quad (17)$$

by substituting $V_t^E - V_t^U = \frac{b}{1-b}V_t^J = \frac{b}{1-b}\frac{\kappa}{(1-\rho)q(\theta_t)}$ and (14) into (15).

Second, substituting each NSC condition (13) for time $t-1$ and t in its equality to (15), we can derive the wage function that satisfies the binding NSC of the previous period and is simultaneously consistent with the committed level of minimum future surplus just enough to induce workers' current effort (the efficiency wage):

$$w_t^E = w^u + e^* + \{E_{t-1}[\frac{1}{\beta(\frac{c_t}{c_{t-1}})^{-\sigma}(1-\rho)}] - E_t[1-p(\theta_{t+1})]\}\frac{e^*}{d} \quad (18)$$

That is, the efficiency wage at period t denotes the minimum wage that fulfills the worker's net surplus for t committed to at $t-1$ and is also consistent with the level of minimum net surplus for $t+1$ committed to at time t.

Then, Lemma 1 will show that in order to satisfy the NSC, all that needs to be done is to ensure that the unconstrained Nash bargaining wage is not lower than the efficiency wage level.

LEMMA 1. *If and only if the NSC is binding (holds in equality) for both period $t-1$ and t, implying $E_i[\beta(\frac{c_{i+1}}{c_i})^{-\sigma}(1-\rho)(V_{i+1}^E - V_{i+1}^U)] = \frac{e^*}{d}$ for $i = t-1$ and t, then $w_t^{NB} = w_t^E$.*

Proof. Under the Nash bargaining, equation (15) is expressed as

$$V_t^E - V_t^U = w_t^{NB} - w^u - e^* + E_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(1-\rho)(1-p(\theta_{t+1}))(V_{t+1}^E - V_{t+1}^U)\} \tag{19}$$

From equation (15), the efficiency wage, the equilibrium wage when the NSC is binding for both period $t-1$ and t, is characterized as

$$w_t^E = w^u + e^* + \{E_{t-1}[\frac{1}{\beta(\frac{c_t}{c_{t-1}})^{-\sigma}(1-\rho)}] - E_t[1-p(\theta_{t+1})]\}\frac{e^*}{d} \tag{20}$$

Subtracting equation (20) from (19) and substituting the NSCs (13) for period $t-1$ and t in their equality leads to $w_t^{NB} = w_t^E$.

By the definition of the efficiency wage w_t^E, it is trivial to show that if $w_t^{NB} = w_t^E$, then the NSCs for period $t-1$ and t are binding. □

LEMMA 2. *If the wage functions (17) and (18) satisfy $w^{NB}(\tilde{x}_t) = w^E(\tilde{x}_t)$, for any $x_t > \tilde{x}_t$, $w^{NB}(x_t) > w^E(x_t)$ holds; by Lemma 1, this means that the NSC is not binding in the current period for any $x_t > \tilde{x}_t$.*

Proof. First, we assume that given any realization of the aggregate productivity shock a_t within a proper domain, there exists the unique threshold level $\tilde{x}_t$ of the idiosyncratic productivity shock that satisfies $w^{NB}(\tilde{x}_t) = w^E(\tilde{x}_t)$, equalizing equations (17) and (18). Since the Nash bargaining wage function $w^{NB}(x_t)$, equation (17), is a strictly increasing function of the idiosyncratic productivity shock x_t while the efficiency wage function $w^E(x_t)$, equation (18), is not related to the idiosyncratic shock (it is affected only by aggregate conditions), for any $x_t > \tilde{x}_t$, $w^{NB}(x_t) > w^{NB}(\tilde{x}_t) = w^E(\tilde{x}_t) = w^E(x_t)$ holds. In other words, for any $x_t > \tilde{x}_t$, the Nash bargaining wage exceeds the efficiency wage level; thus, by Lemma 1, the NSC does not bind in the current period. □

These lemmas imply that in order to induce workers to exert an appropriate amount of effort, firms have only to pay an ordinary Nash bargaining wage whenever it exceeds a committed level of the efficiency wage. Only when the level of the unconstrained Nash bargaining wage is lower than the efficiency wage (when the NSC is binding), firms are forced to pay a wage at least above the efficiency wage level. Thus, the efficiency motivation works asymmetrically. Following shocks that require cuts in the level of the unconstrained Nash bargaining wage relative to the efficiency wage, the downward rigidity arising from the efficiency motivation becomes more prominent. For example, adverse shocks can strengthen the downward wage rigidity more firmly than favorable shocks can, although there is less moral hazard because of a shrink in worker's outside options.[11]

Now, using the threshold idiosyncratic productivity $\tilde{x}_t$, we can characterize the total expected wage function on the firm's side. First, the solution of the condition $w^{NB}(\tilde{x}_t) = w^E(\tilde{x}_t)$ determines the threshold productivity $\tilde{x}_t$. By subtracting equation (18) from (17),

$$bE_t\{\beta(\frac{c_{t+1}}{c_t})^{-\sigma}[\frac{\kappa}{q(\theta_{t+1})} - \frac{1-b}{b}(1-\rho)(1-p(\theta_{t+1}))(V^E_{t+1} - V^U_{t+1})]\}$$

$$= \{E_{t-1}[\frac{1}{\beta(\frac{c_t}{c_{t-1}})^{-\sigma}(1-\rho)}] - E_t[1-p(\theta_{t+1})]\}\frac{e^*}{d} - b(mc_t a_t \tilde{x}_t \bar{e} - w^u - e^*) \quad (21)$$

By Lemma 2, the type of wage function for a certain job depends on whether its realized idiosyncratic shock x_t is higher or lower than the threshold productivity $\tilde{x}_t$. Since each firm consists of a continuum of many ex-ante identical jobs, a firm's total wage payment depends on the distributional properties of the idiosyncratic shock x_t, which are characterized by the cumulative distribution function $F(x)$.

Let's define γ_t as the probability that the NSC is binding (so that firms are forced to pay at least the efficiency wage). By Lemmas 1 and 2, γ_t can be expressed as

$$\gamma_t = Pr(w^{NB}_t \leq w^E_t) = Pr(x_t \leq \tilde{x}_t) = F(\tilde{x}_t) \quad (22)$$

Among n_{it} workers employed by firm i, a fraction γ_t of jobs pay the efficiency wage, while a fraction $1-\gamma_t$ of jobs pay the Nash bargaining wage. Now, a firm's

[11] Notice that the level of efficiency wage increases in the value of outside options for workers. When better outside options are available for workers, firms have to pay a higher wage to induce them not to shirk.

total expected wage can be written as

$$\bar{w}_t = \gamma_t E_t(w_t^E | x_t \leq \tilde{x}_t) + (1-\gamma_t) E_t(w_t^{NB} | x_t > \tilde{x}_t) \tag{23}$$

As shown in equation (18), the efficiency wage level w_t^E is determined independently of the realized level of the idiosyncratic shock x_t. Thus, $E_t(w_t^E | x_t \leq \tilde{x}_t) = E_t(w_t^E)$ holds. However, as seen in equation (17), the expected level of the Nash bargaining wage w_t^{NB} relies on the distribution of x_t conditional on $x_t > \tilde{x}_t$, which takes a truncated log-normal by the log-normality of x_t. Using the properties of a truncated log-normal distribution, the expected value of x_t, conditional on its being larger than the threshold level $\tilde{x}_t$, can be expressed as

$$E(x_t | x_t > \tilde{x}_t) = \exp(\frac{\sigma_x^2}{2}) \frac{\Phi(\sigma_x - (\ln \tilde{x}_t / \sigma_x))}{\Phi(-(\ln \tilde{x}_t / \sigma_x))}$$

where $\Phi(\bullet)$ is a cumulative distribution function of standard normal distribution. Substituting this into equation (17), the conditional Nash bargaining wage $E_t(w_t^{NB} | x_t > \tilde{x}_t)$ can be written as

$$E_t(w_t^{NB} | x_t > \tilde{x}_t) = (1-b)(w^u + e^*) + b\{mc_t a_t \bar{e} \exp(\frac{\sigma_x^2}{2}) \frac{\Phi(\sigma_x - (\ln \tilde{x}_t / \sigma_x))}{\Phi(-(\ln \tilde{x}_t / \sigma_x))}$$

$$+ E_t[\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(\frac{\kappa}{q(\theta_{t+1})} - \frac{1-b}{b}(1-\rho)(1-p(\theta_{t+1}))(V_{t+1}^E - V_{t+1}^U))]\}$$

Combining the total expected wage function (equation (23)) with the labor demand condition (8), we can characterize the labor market equilibrium condition as

$$\frac{\kappa}{q(\theta_t)} = (1-\rho)[mc_t a_t \bar{x}_t \bar{e} - \gamma_t E_t(w_t^E) - (1-\gamma_t) E_t(w_t^{NB} | x_t > \tilde{x}_t)]$$

$$+ E_t[\beta(\frac{c_{t+1}}{c_t})^{-\sigma}(1-\rho)\frac{\kappa}{q(\theta_{t+1})}] \tag{24}$$

Meanwhile, to see the implications of wage rigidity more clearly, we construct an artificial economy where the efficiency wage is not time-varying as in equation (18), but fixed at its steady-state constant level $\bar{w}$. In this economy (fixed efficiency wage model), the wage equation (23) can be rewritten as,

$$\bar{w}_t = \gamma_t \bar{w}^E + (1-\gamma_t)E_t(w_t^{NB}|x_t > \tilde{x}_t) \tag{23$'$}$$

where $\tilde{x}_t$ and γ_t satisfy $w_t^{NB}(\tilde{x}_t) = \bar{w}^E$ and $\gamma_t = Pr(w_t^{NB} \leq \bar{w}^E) = Pr(x_t \leq \tilde{x}_t)$ (see equations (21) and (22)). Thus in this economy, the pro-cyclicality of efficiency wage level is totally removed, so that we can identify the cyclical implication of downward wage rigidity in a more significant manner. The motivation for constructing this artificial economy is, as afore-mentioned, based on the conjecture that in reality there may exist some institutional and economic factors that hinder the flexible adjustment of the efficiency wage level.

3.5. GOVERNMENT AND MONETARY POLICY

The government levies a lump-sum tax τ_t and issues a nominal bond b_t, which pays a gross nominal interest rate R_t one period later, in order to finance the government spending g_t and satisfy the following budget constraint each period:

$$g_t + R_{t-1}\frac{b_{t-1}}{p_t} = \frac{\tau_t}{p_t} + \frac{b_t}{p_t}$$

In a balanced growth path, the government spending g_t is assumed to share a common deterministic trend with real output y_t, and we assume away the presence of any stochastic component in the government spending. Thus, abstracting away from the deterministic trend, the government spending g_t becomes a constant fraction of the steady-state real output, $g_t = s_g y^*$, where y^* is the steady-state value of real output and s_g is the steady-state ratio of government consumption expenditure to total real output.

Monetary policy is described by the following Taylor rule:

$$\frac{R_t}{R^*} = [(\frac{\pi_t}{\pi^*})^{\gamma_\pi}(\frac{y_t}{y^*})^{\gamma_y}]m_t \tag{25}$$

where R^*, π^* , and y^* are the steady-state gross interest rate, the target inflation rate, and the steady-state real output level representing potential output, respectively. The monetary policy shock m_t evolves through

$$\ln m_t = \rho_m \ln m_{t-1} + \varepsilon_t^m, \quad \varepsilon_t^m \sim N(0, \sigma_m^2)$$

3.6. MODEL EQUILIBRIUM

The resource constraint of the economy can be expressed as follows:

$$y_t = a_t n_t \bar{x}_t \bar{e} = c_t + g_t + \kappa v_t + \frac{\varphi}{2}(\pi_t - 1)^2 \tag{26}$$

where y_t, c_t, n_t, and v_t are aggregate real output, consumption, employment, and total number of vacancies at time t, respectively.[12]

A decentralized equilibrium of the model economy is characterized by a sequence of allocation and prices $\{c_t, n_t, v_t, \theta_t, \tilde{x}_t, \gamma_t, \pi_t, mc_t, R_t, \bar{w}_t, w_t^{NB}, w_t^E\}_{t=1}^{\infty}$ satisfying equations (3), (5), (6), (9), (17), (18), (21), (22), (23), (24), (25) and the resource constraint (26) for a given set of aggregate shock processes $\{a_t, m_t\}_{t=0}^{\infty}$ and initial states n_0 . In the fixed efficiency wage model, the condition (18) and (23) are replaced with $w_t^E = \bar{w}^E$ and equation $(23)'$, respectively.

4. QUANTITATIVE ANALYSIS

4.1. CALIBRATION

Except for the efficiency wage arrangement, calibration of most parameters is mainly based on Faia (2008, 2009). The time period is measured in quarters, and we set the discount factor $\beta = 0.99$, so that the annual interest rate in the steady state is about 4%. We choose a standard value for the inverse of the intertemporal elasticity of consumption, $\sigma = 2$. The mark-up of prices over marginal cost is set equal to 20%, implying $\eta = 6$. The price adjustment cost parameter is set to $\varphi = 20$, following Faia (2009), who based her calibration on the observed sensitivity of inflation to marginal costs (see Lubik and Schorfheide (2004)).

The unemployment elasticity of matching, ξ, is set to 0.6, which is the median of the range of estimates that Petrongolo and Pissarides (2001) have reported. Following standard practice in the literature, we set the worker's bargaining power parameter b equal to ξ so that it can satisfy the Hosios (1990) condition. The steady-state worker finding rate, $q(\theta)$, is set to 0.7, following Den Haan et al. (2000). The exogenous separation rate, ρ, is set to 0.1, consistent with Abowd and Zellner's (1985) measurement from 1972-1982 data (3.42% per month). Following Faia (2009), The steady-state employment rate is set to

[12]The aggregate output y_t is defined by CES aggregator, i.e. $y_t \equiv [\int_0^1 (y_{it})^{(\eta-1)/\eta} di]^{\eta/(\eta-1)}$. By symmetry across firms, let $n_{it} = n_t$ and $v_{it} = v_t$ for all i. This leads to $n_t = \int_0^1 n_{it} di$ and $v_t = \int_0^1 v_{it} di$.

$n = 0.6$, which corresponds to the average employment-population ratio in the U.S. during 1964Q1-2011Q4. This implies that we normalize working-age population, instead of labor forces, to one; thus, we are adopting a broader definition of searching workers which includes not only officially unemployed workers, but also all the potential participants that are now out of the labor forces, such as discouraged workers and workers loosely attached to the labor force.[13] It may be more convincing than limiting searching workers to the officially unemployed, considering the fact that a remarkable number of the new hired workers do not transit through the pool of officially defined unemployed workers (See Blanchard and Diamond (1990)).

With given $q(\theta)$, n, and ρ, the steady-state vacancy ratio, v, can be obtained by solving equation (5) in the steady state. Given those calibrated values, the matching efficiency parameter, ζ, is obtained from the steady-state relationship, $\zeta = \rho n \theta^{\xi}/(v(1-\rho))$. The value for the vacancy posting cost, κ, is obtained by solving the steady-state version of the labor market equilibrium condition (equation (8)) in the Nash bargaining model economy. The value of non-market utility, w^u, is set so as to generate the steady-state ratio, $w^u/\bar{w}$, of 0.6[14] in the Nash bargaining model economy, which corresponds to the average net replacement rates (2001-2010) for the households earning the average income in the U.S. (see OECD (2012)). For a fair comparison of the models, the same values of w^u and κ are calibrated to the efficiency wage economy.

As for the parameters characterizing the efficiency wage scheme, we set the shirking detection probability d to 0.05 and normalize the inputted effort level $\bar{e}$ to 1. Given this normalization, we obtained the disutility (in consumption unit) from exerting effort, e^*, by solving the steady-state version of condition (21).

Following the main RBC literature, the innovation process for the aggregate productivity shock a_t is calibrated such that its standard deviation is set to $\sigma_a = 0.007$ and its persistence to $\rho_a = 0.95$. As in Thomas (2011), the standard deviation of the innovation to monetary policy shocks, σ_m, is calibrated to match the standard deviation of real output in the model economy (the Nash bargaining economy) to the data. The standard deviation of the (logged) idiosyncratic shock, σ_x, is set to 0.13 following Walsh (2005), who based his calibration on the relative volatility of job destruction to output in the U.S. data. This value is

[13]This value is consistent with those used in some of the major literature; for instance, Cooley and Quadrini (2004) and Andolfatto (1996) set $n = 0.57$. The qualitative properties of the models are not sensitive across a wide range of values for the steady-state employment rate.

[14]Note that this level of the steady-state ratio lies between the two extremes among previous related studies: Shimer's (2005), $w^u/\bar{w} = 0.4$, and Hagedorn and Manovskii's (2008), $w^u/\bar{w} = 0.977$.

consistent with those in Den Haan et al. (2000) and Krause and Lubik (2007), who use 0.10 and 0.12, respectively.

We consider the monetary policy rule which is a standard Taylor rule with a higher weight on inflation, $\gamma_\pi = 3$ and $\gamma_y = 0.5/4$ (divided by four to redefine the annual GDP gap on a quarterly basis), the same as the strict inflation targeting rule in Faia (2009); by doing so, we can match the standard deviation of the nominal interest rate in the model economy (the Nash bargaining economy) to the data.[15] s_g is set to 0.2, which corresponds to the average ratio of final consumption expenditure of government relative to total final consumption expenditure in the U.S. (1970-2010).

We numerically compute the impulse response and implement the dynamic simulation by solving second-order approximations to the optimal policy function around a non-stochastic steady state, based on the perturbation method of Schmitt-Grohe and Uribe (2004).

4.2. IMPULSE RESPONSES

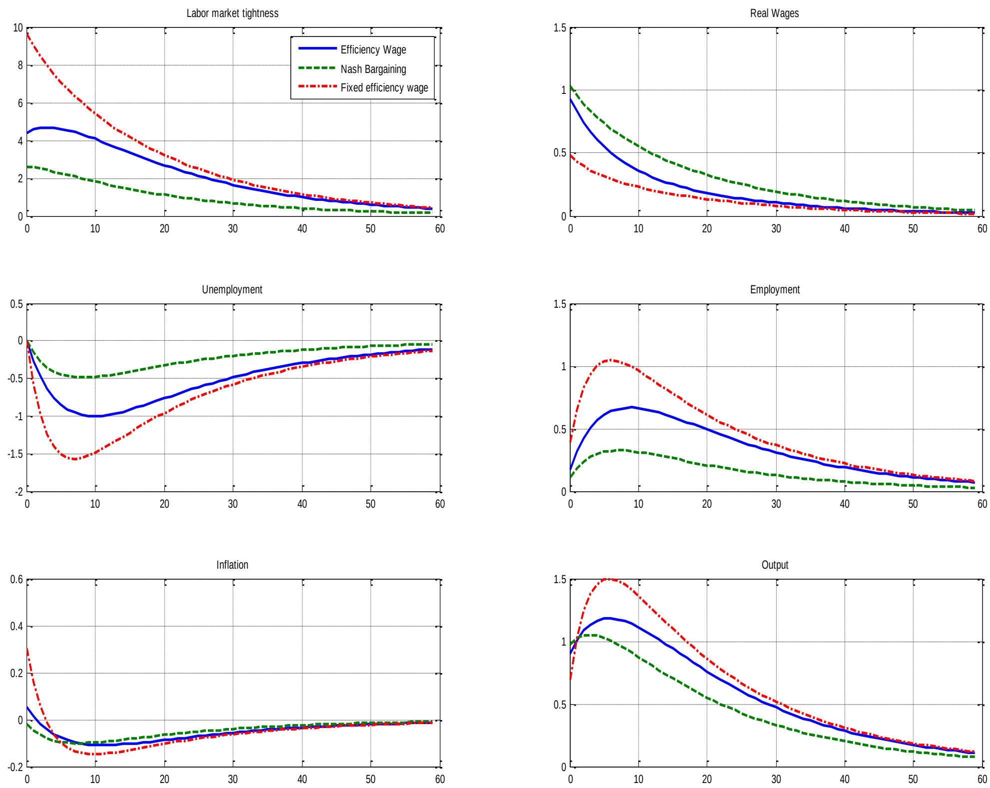
From this section on, we present the distinguished features of our efficiency wage models, compared with the standard Nash bargaining model. First in this section, the impulse responses of each model will be evaluated. Our model's behavior in response to aggregate productivity and monetary policy shocks documents the fact that the real wage rigidity induced by the efficiency wage scheme significantly amplifies the volatilities of labor market quantities and dampens real wage fluctuations, thus addressing the Shimer's (2005) volatility puzzle.

The impulse responses of each model (standard Nash bargaining model, baseline efficiency wage model, fixed efficiency wage model) are depicted in Figures 2 and 3. Consider first the effects of a 1% increase in aggregate productivity. The impulse responses of selected variables are depicted in Figure 2. In the face of a positive productivity shock, vacancy and employment rise and the unemployment rate falls; thus, labor market tightness markedly goes up. Compared with the standard Nash bargaining model, introducing the efficiency wage scheme makes wage responses more muted and thus amplifies fluctuations in vacancies, unemployment, and market tightness, as pointed out by Shimer (2005) and Hall (2005).

Consider next the effects of a $1\%p$ increase in the monetary policy rate. The impulse responses of selected variables are depicted in Figure 3. In the face

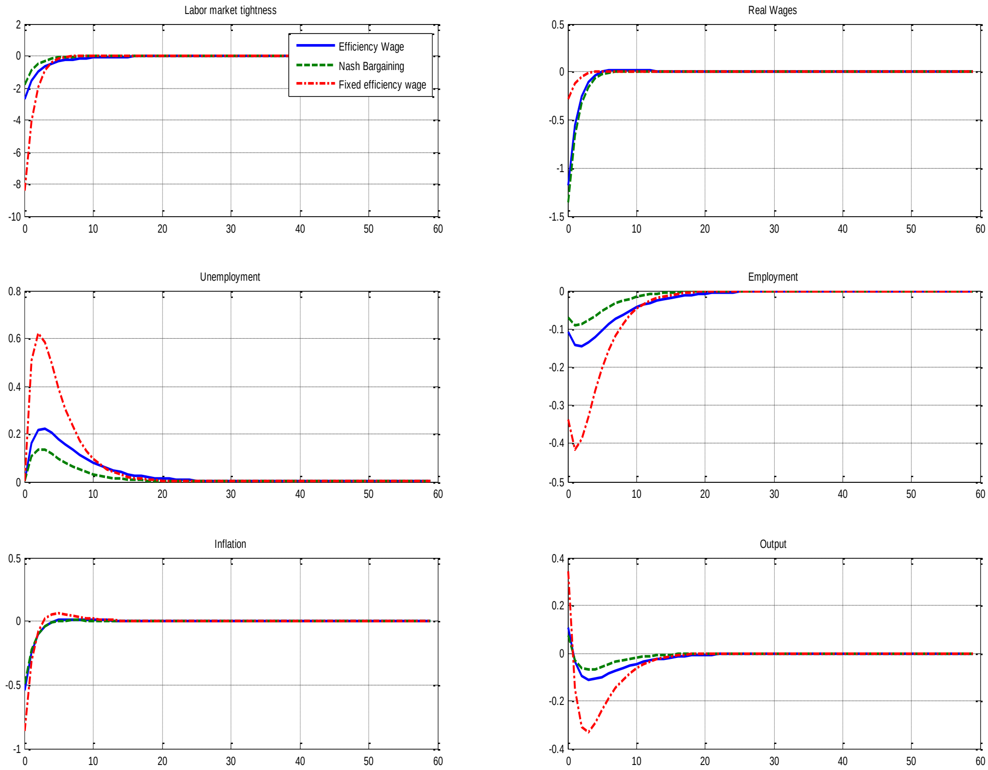
[15] Considering the standard Taylor rule with $\gamma_\pi = 1.5$ and $\gamma_y = 0.5/4$ does not change the qualitative nature of our main results, except that it amplifies the volatilities of some price variables too much to be comparable to those in the data.

Figure 2: Impulse responses of selected variables to aggregate productivity shocks



Note: The solid line and the dashed line denote the impulse responses of the baseline efficiency wage model and the Nash bargaining model, respectively. The red dash-dot line denotes the responses of the fixed efficiency wage model. They depict the responses to a 1% increase in aggregate productivity.

Figure 3: Impulse responses of selected variables to monetary policy shocks



Note: The solid line and the dashed line denote the impulse responses of the baseline efficiency wage model and the Nash bargaining model, respectively. The red dash-dot line denotes the responses of the fixed efficiency wage model. They depict the responses to a 1%p increase in the monetary policy rate.

of a recessionary monetary policy shock (increase in the interest rate), vacancy and employment fall and the unemployment rate rises; thus, labor market tightness markedly goes down. As in the case of aggregate productivity shocks, the efficiency wage scheme significantly amplifies fluctuations in vacancies, unemployment, and market tightness, as it dampens wage responses.

One thing to note is about differences in inflation responses; in response to a positive productivity shock, inflation falls only sluggishly across all the models, which contrasts with an immediate fall in inflation as observed in previous structural VAR literature. This is because there are some forces that fully offset a decrease in real unit costs induced by the positive productivity shock, such as an immediate wage hike resulting from higher labor productivity and a sharp increase in job posting and hiring costs due to higher labor-market tightness. Sluggishness in inflation responses is more striking in the efficiency wage models, mainly because an amplified response in vacancies increases job posting and hiring costs more sharply, thus it reinforces this offsetting effects. Owing to the higher offsetting effect, inflation varies more sluggishly and reaches its trough a bit later than in the standard Nash bargaining model. On the other hand, in response to a recessionary monetary shock, inflation falls immediately. This difference is due to the absence of the offsetting forces; upon the impact of a recessionary monetary shock, vacancy posting and labor market tightness markedly go down and real wage significantly decreases. Thus, those variables vary in the same direction as inflation responding to a monetary shock, while in the opposite direction responding to a productivity shock.

By fixing the efficiency wage, we can confirm the former baseline results more clearly. The fixed efficiency wage model generates a much higher magnitude of amplification in employment and vacancies than the baseline efficiency wage model does, and its dampening effect on real wage becomes more striking.

To sum up, the real wage rigidity induced by the efficiency wage scheme significantly amplifies the volatilities of labor market quantities (employment and vacancies) and real output while it dampens real wage fluctuations, as indicated by Shimer (2005) and Hall (2005). Fixing the efficiency wage generates even a higher magnitude of amplification in employment and vacancies, and its dampening effect on real wage is more striking.

4.3. SIMULATION RESULTS

In this section, business cycle statistics from the data are compared with the corresponding statistics from the simulated model. Moment comparison reveals two main results: first, it evidently shows that the efficiency wage scheme significantly amplifies the volatilities of labor market quantities and dampens real wage fluctuations. This confirms the results of the impulse response analysis. Second, and more important, downward real wage rigidity arising from the incentive consideration can generate the asymmetric behavior of inflation as well as labor market quantities along the business cycle, and the generated asymmetry has an order of magnitude comparable to that observed in the data.

Consider first the volatilities of the main variables in the model. The simulated moments of selected variables are summarized in Table 2. The efficiency wage scheme makes the volatility of unemployment and market tightness more than double while reducing that of real wages to about 75% of that in the standard Nash bargaining model. This amplification also carries over to the relative volatilities against output. This tendency becomes more striking in the fixed efficiency wage model; the fixed efficiency wage makes the volatility of unemployment and market tightness more than three times as high as in the standard model while reducing that of real wages to about 50% of that in the standard Nash bargaining model. However, amplification is not enough, since the baseline efficiency wage model still generates smaller (absolute and relative) volatilities in employment and vacancies than observed in the data.[16] Only when the efficiency wage is fixed are those volatilities comparable to the data.

Now, we turn to the cyclical co-movement of the main variables in the model. Considering the correlation of the main variables with real output in Table 3, both the standard Nash bargaining model and the efficiency wage model usually generates the same direction of correlation as in the data, except for inflation and the nominal interest rate. The models exhibit a Beveridge curve relation, implying a negative correlation between unemployment and vacancies.

There are two things to note: first, incorporating wage rigidity through the efficiency wage scheme makes the real wage become more acyclical over the business cycle, while it exhibits strong pro-cyclicality in the standard Nash bargaining model. We can see that the efficiency wage model significantly reduces the correlation coefficient of the real wage with output, making it comparable to the data, particularly in the case of the fixed efficiency wage. Second, all the models exhibit a negative correlation between output and inflation and between output and the nominal interest rate, contrary to the data in which both inflation and the nominal interest rate seem to be almost acyclical.[17] This is due

[16]Contrary to the data, the volatility of consumption is higher than that of real output across all the model-simulated series. It is because in the model there is no physical capital and investment is subsumed into consumption. Thus, it is inappropriate to simply compare the model-simulated consumption with the data, one-to-one.

[17]Krause and Lubik (2007) also report a negative correlation between output and inflation,

Table 2: Simulated moments(standard deviation)

SD(%) (rel. SD to y)	U.S. data	Model		
		Nash bargaining	Efficiency wage	Fixed efficiency wage
n	2.4 (0.969)	0.8(0.317)	1.7(0.560)	2.6(0.703)
u	2.9 (1.172)	1.2(0.474)	2.6(0.839)	3.9(1.046)
θ	21.2(8.505)	5.6(2.228)	11.8(3.848)	19.3(5.220)
v	18.8(7.557)	4.6(1.836)	9.5(3.126)	16.3(4.433)
π	0.4 (0.144)	0.3(0.120)	0.3(0.113)	0.6(0.167)
r	0.5 (0.218)	0.5(0.194)	0.6(0.204)	1.4(0.411)
w	1.7 (0.674)	1.9(0.761)	1.4(0.496)	1.0(0.290)
y	2.5 (1.000)	2.5(1.000)	3.1(1.000)	3.6(1.000)
c	2.4 (0.959)	3.2(1.249)	3.8(1.250)	4.6(1.251)

Note: The sample period for the data is 1964Q1-2011Q4. Numbers in parentheses are the ratios of the standard deviation of each variable to that of output. Statistics for the model economies are computed by simulating the model 500 times for 200 periods. The statistics are averaged over the 500 simulations.

Table 3: Simulated moments(correlation with real output)

Correlation with y	U.S. data	Model		
		Nash bargaining	Efficiency wage	Fixed efficiency wage
n	0.832	0.955	0.968	0.968
u	-0.819	-0.905	-0.932	-0.965
θ	0.772	0.988	0.988	0.849
v	0.745	0.966	0.966	0.772
π	0.188	-0.772	-0.693	-0.495
r	0.216	-0.781	-0.538	-0.295
w	0.554	0.946	0.838	0.665
y	1.000	1.000	1.000	1.000
c	0.910	0.999	0.999	0.999

to the dominating effect of productivity shocks over monetary shocks, and this dominance is closely related to the model's inability to generate inflation inertia and the persistent effects of monetary shocks, commonly pointed out as a main shortcoming of the standard New Keynesian model. However, as the real wage becomes more rigid, the counter-cyclicality of inflation and the nominal interest rate in the model also becomes gradually weaker.

Now, let's turn to the implications of the efficiency wage for cyclical asymmetry by analyzing the third moments of the simulated data. As in Table 1, the U.S. data indicate that most of the main quantity variables (such as employment, vacancy, and real output) exhibit significant negative skewness, whereas most of the price variables (such as the nominal interest rate, inflation, and real wage) exhibit positive skewness, implying that in recessions employment and vacancies decrease more strongly than they increase in booms, whereas in booms wages and prices increase more strongly than they decrease in recessions.

Table 4 summarizes the skewness of the simulated series in the model. As shown in the second column of Table 4, the asymmetry observed in the data cannot be captured by the standard Nash bargaining model. The skewness es-

although its magnitude is small.

Table 4: Simulated moments(skewness)

Skewness	U.S. data	Model		
		Nash bargaining	Efficiency wage	Fixed efficiency wage
n	-0.325	-0.036	-0.274	-0.972
u	0.202	-0.003	0.194	0.873
θ	-0.507	-0.033	-0.270	-1.181
v	-0.534	-0.046	-0.300	-1.269
π	0.970	0.093	0.184	0.975
r	0.954	0.143	0.354	0.754
w	0.567	-0.014	0.004	1.554
y	-0.536	0.004	-0.081	-0.488
c	-0.428	-0.024	-0.108	-0.514

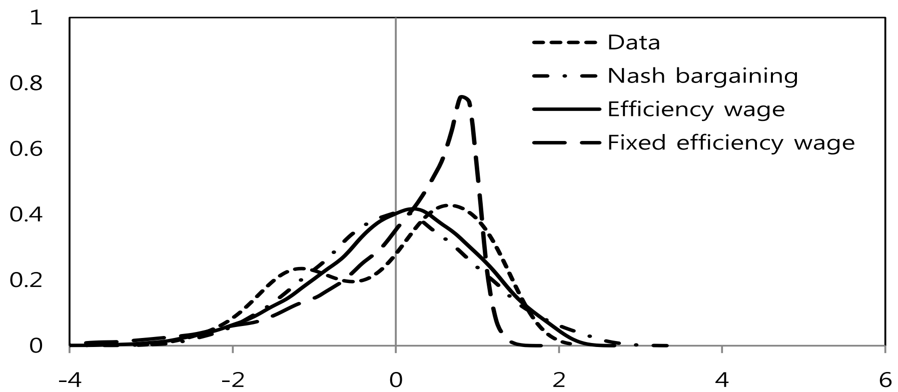
timates of most of the simulated variables are basically zero, and the estimates for unemployment, real wage, and output are even of opposite signs to those for their empirical counterparts. Meanwhile, by introducing the efficiency wage scheme accounting for downward wage rigidity, the model (the third column) is not only able to exhibit the correct direction of skewness but is also able to match the degree of skewness of some main variables well, especially labor market quantities and inflation. Following a shock that requires cuts in wages and discourages job creation, the downward rigidity arising from the efficiency motivation makes wages adjust more sluggishly—leading to more sluggish decreases in inflation—which further reduces the incentive for opening vacancies. In contrast, a relatively stronger increase in real wages—leading to faster increases in inflation—in booms implies that more of the additional surplus is attributed to workers, which significantly attenuates the incentive to post new jobs. This consequent negative skewness of vacancies is directly transmitted to employment. The opposite skewness of unemployment highlights the strong link between unemployment and vacancies through the Beveridge curve. Considering that labor constitutes the only input to production in the model, it is natural that the negative skewness of employment should prevail in shaping the adjustment of output and consumption. In the case of the fixed efficiency wage, this asymmetry becomes more prominent even beyond the level observed in the data, indicating that the real-world labor market lies at some mid-point between the flexible efficiency wage model and the fixed efficiency wage model.

One thing to note is that even though the real wage rigidity is the only source of asymmetry in the model, the real wage itself does not exhibit strong asymmetry as observed in the data. This point can be confirmed by comparing the skewness of real wages between the baseline efficiency wage model (the second column) and the fixed efficiency wage model (the third column). We can see that fixing the efficiency wage to a constant level remarkably increases the degree of positive skewness, even beyond the level observed in the data. This is also consistent with the afore-mentioned conjecture that there may exist other sources that hinder the flexible adjustment of the efficiency wage level.

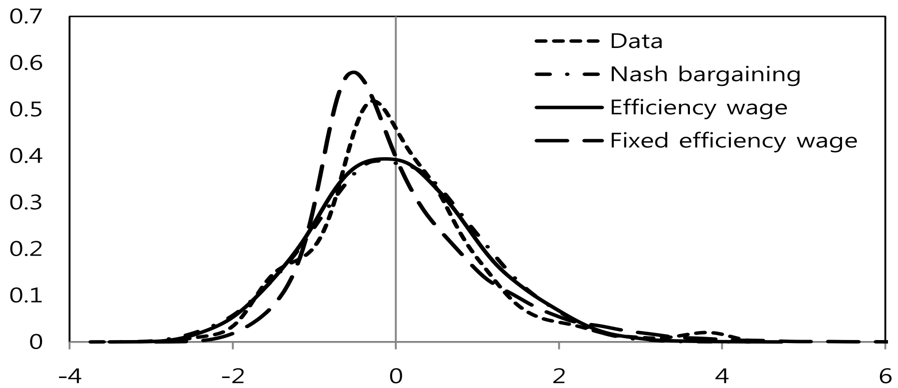
To visualize the cyclical distributions of main quantity and price variables, Figure 4 plots the kernel density estimates of the vacancy/unemployment ratio (θ) and inflation (π) using a Gaussian kernel with optimal bandwidth. Contrary to the data, the Nash bargaining economy generates almost symmetric distributions for both variables, whereas the efficiency wage model exhibits a more left-skewed distribution for the vacancy/unemployment ratio and a more right-skewed distribution for inflation, so that both distributions become a bit closer to the data distribution. Fixing the efficiency wage brings this asymmetry to an extreme, even beyond the level observed in the data. This also indicates that the real-world economy may be located somewhere between the baseline efficiency wage model and the fixed efficiency wage model.

Figure 4: Kernel density estimates for vacancy/unemployment ratio and inflation

Vacancy/unemployment ratio



Inflation



Note: The sample period for the data is 1964Q1-2011Q4. For proper scaling, all the series are standardized before estimating kernel density. Thus, the measurement unit on the x-axis is one standard deviation of each corresponding variable.

5. CONCLUDING REMARKS

This paper develops a variant of the New Keynesian model with the Mortensen-Pissarides search frictions by incorporating downward real wage rigidity based on the efficiency wage framework of Shapiro and Stiglitz (1984). When we examine the cyclical implications of the wage rigidity induced by the efficiency wage scheme for labor market and inflation dynamics, we find that introducing downward wage rigidity can generate the asymmetric dynamics of inflation as well as labor quantities observed in the data. Therefore, the model can resolve the counterfactual symmetry commonly featured in the standard New Keynesian and equilibrium search model. Furthermore, real wage rigidity significantly amplifies the volatilities of labor market quantities and dampens real wage fluctuations. Thus, it can address Shimer's (2005) volatility puzzle and explain the observed weak cyclicality of real wage dynamics.

One caveat to note is that the model exhibits a limited performance in explaining the shock responses of inflation; in response to a positive productivity shock, inflation falls only sluggishly in the model, which contrasts with an immediate fall in inflation as observed in previous structural VAR literature. This is because of the offsetting forces that fully countervail a decrease in real unit costs induced by the positive productivity shock, such as a sharp increase in job posting and hiring costs due to higher labor-market tightness. Further research should address this inconsistency in inflation dynamics.

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