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Labor market dynamics under long-term wage contracting ☆

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ABSTRACT

Recent research seeking to explain the strong cyclicality of US unemployment emphasizes the role of wage rigidity. This paper proposes a micro-founded model of wage rigidity—an equilibrium business cycle model of job search, where risk neutral firms post optimal long-term contracts to attract risk averse workers. Equilibrium contracts feature wage smoothing, limited by the inability of parties to commit to contracts. The model is consistent with aggregate wage data if neither worker nor firm can commit, producing too rigid wages otherwise. Wage rigidity does not lead to a substantial increase in the cyclical volatility of unemployment.

1. Introduction

In recent years significant research effort has been devoted to trying to understand the sources of the strong cyclical volatility of unemployment in the US. The standard tool for modeling unemployment, the Mortensen–Pissarides search and matching model (Pissarides, 1985), produces significantly smaller variation in unemployment than observed (Shimer, 2005a). This gap between model and data has led to the view that the observed cyclicality of unemployment is a manifestation of important rigidities affecting wage determination, suggested by the weak cyclicality of aggregate wage data, and not captured by the model (Hall, 2005). However, while imposing exogenous rigidity in wages easily allows the model to produce much larger variation in unemployment, mechanically explaining the puzzle, it does not provide a satisfactory economic answer to the problem. It is well known that outcomes in macroeconomic models with exogenously imposed rigidities can differ substantially from those in models where rigidities are derived from micro-foundations.[1] This paper shows that wage rigidity, as derived from a plausible microeconomic foundation and embedded into an equilibrium

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[1] For a striking example in the context of price-setting in the face of menu costs, Caplin and Spulber (1987) illustrate that the real effects of monetary shocks vanish when firms are allowed to optimize in price-setting, rather than being exogenously constrained.

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model, need not lead to a substantial increase in the cyclical volatility of unemployment. By considering the impact of limited commitment as a contracting friction affecting wage determination in the model, I show that aggregate wage data are not informative about the measure of wage rigidity relevant for unemployment cyclicality.

This paper develops an extension of the Mortensen–Pissarides model, where risk neutral firms use optimal long-term contracts to attract risk averse workers. Labor markets are subject to search frictions, but operate competitively (Moen, 1997). To attract workers, firms post vacancies. A vacancy specifies a long-term wage contract and the firm's choice of contract balances the costs of paying high wages with the benefits of attracting many job applicants. Unemployed workers observe all contracts offered and choose one to apply for, balancing the benefits of high wages with the costs of having to search longer for such jobs. Labor productivity varies over the business cycle and, when risk averse workers cannot smooth consumption privately, efficient wage contracts feature income smoothing. Jobs end due to idiosyncratic separation shocks, leaving the worker to face unemployment on his own, without protection from former employers. The ability to commit to contracts affects equilibrium outcomes. Under commitment, insurance motives lead to a constant contract wage, but when parties cannot commit, their outside options restrict the degree of wage smoothing possible. Three cases are studied: two-sided commitment, one-sided commitment, and two-sided limited commitment. In addition to affecting the cyclicality of the aggregate wage through its effect on wage contracts, the ability to commit also has allocative effects on vacancy creation.

The quantitative results show that with the exception of the two-sided limited-commitment contracting environment, the model produces an aggregate wage which is very rigid compared to data. Wage rigidity does not come with the substantial increase in the cyclical volatility of unemployment seen in the context of exogenously imposed rigidity, however. Limited commitment works to increase the cyclicality of both the aggregate wage and unemployment, bringing the model closer to data on both dimensions. These seemingly surprising results have a simple explanation: Wage smoothing within contracts translates into significant rigidity in the aggregate wage, but it does not imply that wages are rigid when it comes to hiring new workers. The relevant statistic for hiring decisions is the present value of wages used to attract new workers. Introducing limited commitment makes the present value more rigid, leading to greater variation in vacancy creation. However, it also leads to pro-cyclical adjustments in contract wages, as well as increased cyclicality in starting wages, both of which increase the cyclicality of the aggregate wage. Finally, the results show that while the impact of limited commitment on the aggregate wage is substantial, the impact on unemployment is relatively modest in magnitude. The findings warn against using aggregate wage data to draw inferences about wage rigidity as the cause of unemployment cyclicality.

The unemployment dynamics of the model differ from the standard Mortensen–Pissarides model for two main reasons. The first has to do with the incomplete markets environment faced by workers. When risk averse workers cannot smooth their consumption across unemployment and employment spells, they gain less from finding a job with a high wage level than they would if they could smooth their consumption. This change in how workers value wages affects the wage contracts firms find optimal to offer, and distorts the equilibrium toward lower wages. In periods when high productivity bids up the wages firms use to attract new workers, the distortion increases, curbing the wage increase. In periods when low productivity causes the wages used to attract new workers to fall, the distortion relaxes, curbing the wage decrease. The resulting rigidity in the present value of wages used to attract new workers translates into increased cyclicality in vacancy creation.[2] The second reason has to do with limited commitment exacerbating the above effects. Under full commitment, firms offer a permanently higher wage to workers hired in booms than those hired in recessions. When limited commitment binds in equilibrium, such contracts are no longer feasible. All the firm can do to raise the wages used to attract new workers in booms is to raise the starting wage, prevailing until the first recession arrives and the firm's participation constraint forces the wage down. Similarly, all the firm can do to lower the wages used to attract new workers in recessions is to lower the starting wage, prevailing until the first boom arrives and the worker's participation constraint forces the wage up. Creating differences in present values across booms and recessions in such an environment has to involve increasing the dispersion in starting wages across the two states. This exacerbates the distortion due to the incomplete markets environment in booms and relaxes it in recessions, adding to the rigidity in the present value of wages used to attract new workers and hence also the cyclicality of vacancy creation.

The principal theoretical contribution of this paper is to embed the two-sided limited-commitment wage contracting problem of Thomas and Worrall (1988) into an equilibrium model of directed search with aggregate shocks.[3] The embedding involves incorporating flows in and out of employment relationships and endogenizing the outside options restricting contracting to reflect the equilibrium value of search. As is well known, solving the

[2] The impact of incomplete markets is discussed in detail in Rudanko (2008).

[3] My model has already been applied by others to study related questions: Reiter (2008) examines business cycles driven by embodied technology shocks and Kudlyak (2007) the cyclicality of wages in individual level data. The empirical studies of Macis (2007) and Haefke et al. (2007) are also closely related. Interestingly, the contracts in the model are also observationally similar to those in MacLeod and Malcomson (1993), with renegotiation by mutual consent. In earlier work, Sigouin (2004) embedded two-sided limited-commitment contracts into an equilibrium model of job search, but in his model unemployment is constant over the business cycle.

two-sided limited-commitment contracting problem is complicated by the relevant recursive representation not being a contraction, a feature which must here be dealt jointly with solving for endogenous outside options.

Section 2 presents the model. Sections 3 and 4 examine its qualitative and quantitative properties, respectively. Section 5 concludes. Supplementary online appendixes provide proofs of theoretical results, a description of the computational approach, and robustness checks.

2. Model

This section develops an extension of the Mortensen–Pissarides model with optimal dynamic long-term wage contracting. The extension involves introducing risk averse workers facing incomplete asset markets into the model, which makes long-term contracting optimal, as well as incorporating directed search, which gives both firms and workers the opportunity to optimally choose a wage contract to offer and apply for.

2.1. Preferences and technologies

There is a continuum of measure one workers with preferences $E_t\sum_{\tau=0}^{\infty}\beta^{\tau}u(c_{t+\tau})$, where u is a CRRA utility function. They consume their income each period, so consumption c equals the wage w if the agent is working and $b>0$ if the agent is unemployed.

There is a continuum of entrepreneurs with preferences $E_t\sum_{\tau=0}^{\infty}\beta^{\tau}c^e_{t+\tau}$, where c^e is the sum of cash flows from firms the entrepreneur owns. Entrepreneurs have free access to a constant returns to scale production technology using labor as the only input. The term firm will be used to refer to a single worker production unit. One entrepreneur can operate an unlimited number of firms.

The output of an operating firm during a period is given by ez, where z is an aggregate shock, and e is a match specific shock. The aggregate shock $z>b$ follows an n state Markov chain with transition probabilities $\pi(z'|z)$, such that the transition matrix Π is monotone. The match specific shock e is equal to one for all new matches and each period with probability δ switches to zero permanently. At that time the match is terminated. The cash flow of an operating firm during a period is $z-w$.

In the beginning of each employment relationship, a state-contingent long-term wage contract is signed. Contracts are assumed to be conditional on aggregate productivity at the time of contracting and specify wages for all continuation histories of z after that, for as long as the match operates. A match history of shocks for a given production unit that starts production in state z_0 and is still producing τ periods later is denoted as $z^{\tau}=(z_0,z_1,\ldots,z_{\tau})$. A wage contract is a set of functions

$$\sigma(z)=\{w_{\tau}(z^{\tau})\in[\underline{w},\overline{w}] \text{ for all } z^{\tau},\tau=0,1,\ldots \text{ s.t. } z_0=z\},$$

where z denotes the state at the time of contracting.

One can then define the utility value of a contract to the contracting parties. Suppose that the market value of unemployment to a worker in aggregate state z is $V^u(z)$. The utility value of a new contract σ in state z is

$$V_{\sigma}(z)=u(w_0(z))+E_z\sum_{\tau=1}^{\infty}\beta^{\tau}(1-\delta)^{\tau-1}[(1-\delta)u(w_{\tau}(z^{\tau}))+\delta V^u(z_{\tau})]. \tag{1}$$

The contract specifies a wage for all continuation histories of z while $e=1$. The separation shock hits each period with probability δ, leading to the worker becoming unemployed and receiving the prevailing value of unemployment. The set of feasible wage contracts, $\Sigma(z,V^u)$, is defined as all $\sigma(z)$ s.t. $V_{\sigma}(z)\geqslant V^u(z)$. The utility value of a new contract cannot be lower than the value of remaining unemployed.

Free entry drives an entrepreneur's equilibrium value of searching for a worker to zero. Hence, the present value of profits for a firm from a new contract σ in state z is

$$F_{\sigma}(z)=z-w_0(z)+E_z\sum_{\tau=1}^{\infty}\beta^{\tau}(1-\delta)^{\tau}(z_{\tau}-w_{\tau}(z^{\tau})). \tag{2}$$

While the match is productive, the firm produces z_{τ} and pays wages $w_{\tau}(z^{\tau})$. Once the separation shock hits, the firm is left with the market value of searching for a new worker, zero.

Workers and firms face search frictions in the labor market, captured by a matching function. To hire a worker, a firm must post a vacancy specifying a wage contract. Posting a vacancy costs the firm k units during each period of search. For unemployed workers, search is costless. Each firm chooses a contract to offer, considering both the present value of wages the contract entails as well as the likelihood of finding a worker, which varies by contract. Each unemployed worker observes all the contracts offered by firms and chooses one to apply for, considering both the value of the contract and the likelihood of getting the job. The labor market can be thought of as segmenting into contract-specific sub-markets. Given a measure N_u unemployed workers applying for contract σ and measure N_v vacancies offering σ, the measure of matches taking place this period is given by a Cobb–Douglas matching function $m(N_u,N_v)=KN_u^{\alpha}N_v^{1-\alpha}$, with $0<K<1$ and $0<\alpha<1$. Defining $\theta=N_v/N_u$ as the contract-specific labor market tightness or vacancy–unemployment ratio, the probability that a worker finds a job this period in this market is $\mu(\theta) := m(N_u, N_v)/N_u$ and the probability that a firm finds a worker $q(\theta) := m(N_u, N_v)/N_v$.[4]

In principle different sub-markets could co-exist at the same time but, as will become clear later, it will not happen in equilibrium. Anticipating such an outcome, the equilibrium definition specifies the labor market as a single $(\sigma(z), \theta(z))$-pair for all z. Nevertheless, one has to consider the *possibility* of alternative markets. Given a value of unemployment $V^u(z)$ for all z, the contract $\sigma(z)$ determines the value to a worker from matching based on Eq. (1), and the market tightness $\theta(z)$ determines the probability of matching, $\mu(\theta(z))$. To maximize utility in the choice of contract to apply for, in the presence of an alternative market, a worker would compare the expected value $\mu(\theta(z))(V_\sigma(z) - V^u(z))$ across the markets. On the firms' side, the contract value $F_\sigma(z)$ is based on Eq. (2) and the probability of matching is $q(\theta(z))$. To maximize profits, in the presence of an alternative market, a firm would compare the expected value $q(\theta(z))F_\sigma(z)$ across the markets.

2.2. A competitive search equilibrium

A competitive search equilibrium is defined along the lines of Moen (1997).

Definition 1. An equilibrium of the economy consists of: for each z, a search value for unemployed workers $V^u(z)$, a market tightness $\theta(z)$ and a wage contract $\sigma(z) \in \Sigma(z, V^u)$ such that

1. Search offers zero profit to an entrepreneur:

$$q(\theta(z))F_\sigma(z) - k = 0,$$

where $F_\sigma(z)$ satisfies (2).

2. No Pareto improving market is possible: $\nexists \hat{\sigma}(z) \in \Sigma(z, V^u)$, and $\hat{\theta}(z) \geqslant 0$, s.t.

$$\mu(\hat{\theta}(z))(V_{\hat{\sigma}}(z) - V^u(z)) > \mu(\theta(z))(V_\sigma(z) - V^u(z))$$

and

$$q(\hat{\theta}(z))F_{\hat{\sigma}}(z) - k > 0,$$

where $V_\sigma(z)$, $V_{\hat{\sigma}}(z)$ satisfy (1) and $F_{\hat{\sigma}}(z)$ satisfies (2).

3. The search values of workers are consistent:

$$V^u(z) = u(b) + \beta \sum_{z'} \pi(z'|z)[\mu(\theta(z'))V_\sigma(z') + (1 - \mu(\theta(z')))V^u(z')].$$

The equilibrium conditions can be thought of as arising from a contract-posting setting, where entrepreneurs are free to post any feasible wage contract and each worker directs his search to a single optimal contract. For the purposes of understanding the connection, fix a state z. Consider then a labor market offering contract σ with prevailing market tightness θ. When a firm considers posting an alternative contract $\hat{\sigma}$, it has beliefs about the market tightness $\theta^B(\hat{\sigma})$ that will prevail in the market for that contract, and will only post $\hat{\sigma}$ if $q(\theta^B(\hat{\sigma}))F_{\hat{\sigma}} - k \geqslant 0$. If a contract $\hat{\sigma}$ were posted, the unemployed workers' choice of contract to apply for would determine $\hat{\theta}$, the tightness of the market for $\hat{\sigma}$. The beliefs of firms are assumed to be consistent with the idea that the measure of workers applying for the alternative contract would be such that workers are made indifferent between applying for the alternative contract $\hat{\sigma}$ and the equilibrium contract σ. If the alternative contract implies a high contract value, many workers apply for it. The more workers apply, the harder it becomes for those workers to get the job, and eventually workers are left indifferent between the two contracts. For (σ, θ) to be an equilibrium, there cannot exist a feasible alternative contract $\hat{\sigma}$ that wouldgive the firm strictly positive profits, given the expected tightness of the market for $\hat{\sigma}$.

The model incorporates some features familiar from the implicit contracts literature following Azariadis (1975) and Baily (1974). One such feature is the assumption of risk averse workers and risk neutral firms, which is based on arguments that: (i) selection into entrepreneurship favors less risk averse agents, (ii) entrepreneurs are wealthier than workers, so may behave as though they are less risk averse, and (iii) entrepreneurs have better access to asset markets so can insure away risk.[5] Another such feature is that workers cannot save privately. This modeling choice is driven by the extensive literature documenting that a large fraction of the population holds relatively little wealth, particularly for short-term consumption smoothing purposes, with a significant fraction exhibiting liquidity constrained behavior. Particularly in modeling the unemployed, a plausible starting point seems to be that on average they are not particularly wealthy individuals. Chetty (2008) shows that approximately half of unemployment benefit claimants in the US held no liquid wealth at the time of job loss, exhibiting liquidity constrained behavior. In models with saving, workers tend to accumulate more wealth than these

[4] In a discrete time model, the matching function may need to be truncated to make sure $\mu(\theta), q(\theta) \leqslant 1$. In practice the parameters will be such that truncation will not be necessary.

[5] Rudanko (2008) explores a setting where also entrepreneurs are risk averse, differing from workers by having better access to asset markets.

observations suggest, causing a discrepancy between the model and data, which directly affects the job search behavior of individuals.[6]

The agents in the model face exogenous shocks to labor productivity, both aggregate and idiosyncratic. The role of the idiosyncratic shock is to proxy for the various reasons why matches sometimes end due to person or match specific factors. Note that the separation rate is constant over time. This simplifying assumption is based on the evidence reported by Shimer (2005b), showing that even though the separation rate is counter-cyclical in the data, its contribution to explaining fluctuations in unemployment is small compared to changes in the job-finding rate, which explain the bulk of the variation. Hence, the aggregate shock does not lead to separations in the model.[7]

3. Equilibrium properties

Equilibrium contracts must be Pareto efficient between worker and firm, and the ability to commit to contracts affects what contracts are feasible. This section begins by analyzing the case of full-commitment contracting, then proceeding to contracting under limited commitment. Because the case of one-sided limited commitment is a relatively simple intermediate case, the analysis tackles directly the case of two-sided limited commitment.

3.1. Wage contracts under commitment

For any state z and feasible worker value V, the Pareto frontier of efficient contracts is defined as

$$f^{FC}(V,z,V^u) = \sup_{\sigma \in \Sigma(z,V^u)} \{F_\sigma(z) | V_\sigma(z) \geqslant V\}.$$

Because a contract on the frontier cannot be Pareto dominated after any history, f^{FC} must satisfy the functional equation

$$\begin{aligned} f^{FC}(V,z,V^u) &= \max_{w,\{V(z')\}} \{z - w + \beta E_z (1-\delta) f^{FC}(V(z'),z',V^u)\} \\ \text{s.t. } V &= u(w) + \beta E_z[(1-\delta)V(z') + \delta V^u(z')], \\ w &\in [\underline{w}, \overline{w}]. \end{aligned} \tag{3}$$

Providing the worker value V is partly accomplished through today's wage w, partly through the value of unemployment and partly through future wages, which determine continuation values $V(z')$ for all the states possible next period. The worker receives $V(z')$ if separation does not occur and the value of unemployment $V^u(z')$ if it does. The maximum firm value from providing $V(z')$ next period is given by $f^{FC}(V(z'),z',V^u)$ and if separation occurs the firm is left with zero.

Definition 2. An equilibrium with *full commitment* is characterized by $V^u(z)$, $\theta(z)$ and $\sigma(z) \in \Sigma(z,V^u)$ $\forall z$, that satisfy parts 1–3 of Definition 1.

Proposition 3. *For any z and $V \geqslant V^u(z)$, there exists a unique efficient contract and $f^{FC}(V,z,V^u)$ is strictly decreasing, strictly concave and continuously differentiable in V.*

Proposition 4. *For any $V \geqslant V^u(z)$, the efficient contract under full commitment has a constant wage throughout the contract.*

The optimal wage contract implements an efficient risk sharing arrangement between worker and firm, by way of a constant contract wage. The Pareto frontier is concave because workers enjoy diminishing marginal utility from increasing the wage level. The proofs of these and other theoretical results in the paper can be found in a supplementary online appendix.

3.2. Unique contract offered in the labor market

Having established that equilibrium contracts lie on the Pareto frontier, thus pinning down the form of the optimal state-contingent contract, the remaining question is how the surpluses from matching are divided between the worker and firm, determining the level of wages paid. To answer this second question, parts 1 and 2 of the definition of equilibrium can

[6] Long-term contracts may well play a role in explaining a part of why wealth holdings are low, given the income smoothing they provide, but this remains an avenue for future research. Solving a model with saving becomes significantly complicated in a business cycle setting, because individual job search decisions depend on individual wealth. Combining these issues with long-term-contracting poses a challenge. However, as pointed out by the referee, it would be quite feasible to examine an economy with two groups of workers: one with access to complete markets (pooling labor income risk through a large household), and one with no access to asset markets.

[7] The aggregate shock can be interpreted as anything affecting labor productivity. One such possibility is a technology shock, but there is no reason to rule out other options such as policy or taste shocks. Clearly the model's ability to match data will be limited by only considering a shock to labor productivity (whatever the sources). The task is to evaluate whether the model's responses to such a shock are consistent with data.

be collapsed to the problem:

$$\max_{V(z),\theta(z)} \mu(\theta(z))(V(z)-V^u(z))$$
$$\text{s.t. } q(\theta(z))f^{FC}(V(z),z,V^u)=k, \tag{4}$$

where existence requires that $V^u(z)$ and k are such that $f^{FC}(V^u(z),z,V^u)\geqslant k$ for all z.

Proposition 5. *Given $V^u(z),k$ such that $f^{FC}(V^u(z),z,V^u)\geqslant k$, (4) has a unique solution.* [8]

For any contract delivering a high value to the worker via high wages, the market tightness must be low for firms to break even in offering such a contract. The low market tightness makes the contract less attractive to workers because their job-finding probability is low. The congestion properties of the labor market, captured by the matching function, imply that as wages rise, the declining job-finding probability eventually begins to dominate the rising contract value to the worker and there is a unique optimal wage level balancing these effects.[9] As the quantitative section will illustrate, both the contract value $V(z)$ and market tightness $\theta(z)$ are increasing in productivity. In booms workers are hired faster and with a higher (constant) wage than in recessions.

Thus, the restriction made in the definition of equilibrium about the labor market featuring a single contract is innocuous because even if one allowed multiple contracts, the equilibrium would only feature one. For comparing the results of this paper to the literature, it is helpful to note the following result on the close connection between the competitive search equilibrium and an economy with bilateral wage bargaining. The result is immediate when comparing the first order conditions of the two problems.

Proposition 6. *The competitive search equilibrium of Definition 1 produces the same equilibrium conditions resulting in an environment where search is undirected and when a worker and firm meet they bargain over a long-term wage contract $\sigma(z)\in\Sigma(z,V^u)$, by maximizing the Nash product $(V_\sigma(z)-V^u(z))^\alpha F_\sigma(z)^{1-\alpha}$, where α is the power of the Cobb–Douglas matching function.*

3.3. Contracting under two-sided limited commitment

The quantitative exercises will show that constant-wage contracts often require commitment on both sides to be feasible. A worker hired in a downturn has a permanently low wage and may prefer to quit in a boom. A firm that hired a worker during a boom with a permanently high wage may prefer to fire the worker in a downturn. If the contracting parties cannot commit, such wage smoothing is not feasible. This section examines contracting when neither the worker nor firm can commit.[10]

Define $V_\sigma(z^\tau)$ as the utility value of an on-going contract σ to a worker, given that the contract has been in operation $\tau>0$ periods and the history of shocks is z^τ. We have

$$V_\sigma(z^\tau)=u(w_\tau(z^\tau))+E_{z^\tau}\sum_{\tilde\tau=\tau+1}^{\infty}\beta^{\tilde\tau-\tau}(1-\delta)^{\tilde\tau-\tau-1}[(1-\delta)u(w_{\tilde\tau}(z^{\tilde\tau}))+\delta V^u(z_{\tilde\tau})].$$

For firms, respectively,

$$F_\sigma(z^\tau)=z_\tau-w_\tau(z^\tau)+E_{z^\tau}\sum_{\tilde\tau=\tau+1}^{\infty}\beta^{\tilde\tau-\tau}(1-\delta)^{\tilde\tau-\tau}(z_{\tilde\tau}-w_{\tilde\tau}(z^{\tilde\tau})).$$

For contracts to be self-enforcing, both workers and firms must always weakly prefer staying in the contract to pursuing their outside option. The set of feasible contracts must hence be restricted as follows:

$$\Sigma^{LC}(z,V^u)=\{\sigma(z)\in\Sigma(z,V^u)|V_\sigma(z^\tau)\geqslant V^u(z_\tau),F_\sigma(z^\tau)\geqslant 0\quad\forall z^\tau,\tau=0,1,\ldots \text{s.t. } z_0=z\}.$$

Definition 7. An equilibrium with *limited commitment* is characterized by $V^u(z)$, $\theta(z)$ and $\sigma(z)\in\Sigma^{LC}(z,V^u)\ \forall z$, that satisfy parts 1–3 of Definition 1.

The Pareto frontier under limited commitment is defined as

$$f^{LC}(V,z,V^u)=\sup_{\sigma\in\Sigma^{LC}(z,V^u)}\{F_\sigma(z)|V_\sigma(z)\geqslant V\},$$

[8] The result holds for more general matching functions than Cobb–Douglas. A sufficient condition is that the elasticity of q is weakly decreasing.

[9] Uniqueness occurs for the same reasons as in Moen (1997), with the concave preferences factoring in to reduce the gain to the worker from high wages.

[10] The quantitative exercises consider also the case where firms can commit, but workers cannot. The one-sided case is relatively straightforward and discussed briefly at the end of the section.

and now f^{LC} must satisfy the functional equation

$$\begin{aligned} & f^{LC}(V,z,V^u) = \max_{w,\{V(z')\}} \{z - w + \beta E_z(1-\delta) f^{LC}(V(z'),z',V^u)\} \\ & \text{s.t. } V = u(w) + \beta E_z[(1-\delta)V(z') + \delta V^u(z')], \\ & V(z') \geqslant V^u(z'), \forall z', \\ & f^{LC}(V(z'),z',V^u) \geqslant 0, \forall z', \\ & w \in [\underline{w}, \overline{w}] \end{aligned} \tag{5}$$

for any feasible V. The above equation is similar to Eq. (3), with two additional constraints. The continuation value of the worker $V(z')$ can never be less than the value of unemployment $V^u(z')$, and the value of the contract to the firm $f^{LC}(V(z'),z',V^u)$ can never be negative.

Proposition 8. *When a constrained efficient contract exists, the set of values for which it exists is a closed and bounded interval* $[V^u(z), \overline{V}(z,V^u)]$. *For any* V *within the interval there is a unique efficient contract, and* $f^{LC}(V,z,V^u)$ *is strictly decreasing, strictly concave and continuously differentiable with respect to* V.

In limited-commitment contracts, the promised values assigned to workers are bounded from below by $V^u(z)$ and from above by the fact that firms must make positive profits. Here $\overline{V}(z,V^u)$ is the promised value delivering zero present value of profits to firms, $f^{LC}(\overline{V}(z,V^u),z,V^u) = 0$. The proof of the above result follows Thomas and Worrall (1988), with small extensions.

Lemma 9. *For any* $V \in [V^u(z), \overline{V}(z,V^u)]$, $(\partial f^{LC}/\partial V)(V,z,V^u) = -1/u'(w)$, *where* w *is the wage the efficient contract specifies for the current period.*

Proposition 10. *For any* $V \in [V^u(z), \overline{V}(z,V^u)]$, *the efficient wage contract is characterized by a wage which is constant unless either participation constraint binds. If* $f^{LC}(V,z,V^u) \geqslant 0$ *binds, the wage is adjusted down just enough to make it hold with equality. If* $V \geqslant V^u(z)$ *binds, the wage is adjusted up just enough to make it hold with equality.*

Lemma 9 states the envelope condition for the recursive representation (5). It relates the current period wage w to the slope of the Pareto frontier at promised value V, establishing a strictly increasing relationship between the two. To see why the optimal contract has the above properties, consider the first order condition for $V(z')$ in the recursive representation: $-1/u'(w) = -(1/u'(w'(z')))(1+\psi(z')) + \eta(z')$, where $\eta(z')$ is the Lagrange multiplier on the worker's participation constraint in state z' and $\psi(z')$ the corresponding multiplier on the firm's constraint. If neither constraint binds, $\eta(z') = \psi(z') = 0$ and constant marginal utility implies a constant wage, $w'(z') = w$. If the worker's participation constraint binds for some future state z', then $\eta(z') > 0, \psi(z') = 0$ implies $w'(z') > w$. If the firm's constraint binds, then $\psi(z') > 0, \eta(z') = 0$ implies $w'(z') < w$. Contract wages remain constant whenever possible, but the participation constraints restrict contract values to the interval $[V^u(z), \overline{V}(z,V^u)]$ for each z. Lemma 9 relates these value intervals to intervals of wages feasible for each aggregate state. The contract wage is constant as long as it lies within the wage interval, but if keeping the wage constant would lead it outside the interval, then the wage adjusts up or down just enough to bring it inside the interval.

Analogous results to Propositions 5 and 6 hold also for limited-commitment contracts. The existence of equilibrium requires $f^{LC}(V^u(z),z,V^u) \geqslant k$ for all z, which is a tighter condition than that a limited-commitment contract exist.

The wage contracts inherit the qualitative features of the contracts in Thomas and Worrall (1988). However, in order to discuss the implications of the contracting framework for unemployment and wages in an economy with turnover in the labor force, my model enriches their environment with flows into and out of employment relationships, as well as allowing the outside options restricting contracting to reflect the equilibrium value of search rather than participation in spot labor markets.

The quantitative exercises also consider the intermediate case of one-sided limited commitment, where only firms can commit to contracts. Imposing the participation constraints only for workers, the feasible set of contracts then becomes

$$\Sigma^{1LC}(z,V^u) = \{\sigma(z) \in \Sigma(z,V^u) | V_\sigma(z^\tau) \geqslant V^u(z_\tau) \quad \forall z^\tau, \tau = 0,1,\ldots \text{ s.t. } z_0 = z\}.$$

In this case efficient wage contracts keep the contract wage constant whenever possible, but if the worker's outside option rises sufficiently, as job-finding rates and the contract values used to attract new workers rise in a boom, the wage is adjusted up just enough to match the outside option. When firms are committed, contract wages never fall.

4. Quantitative results

This section examines the quantitative performance of the model and the impact of commitment on business cycle variation in unemployment, vacancies and wages. The solution method is discussed in a supplementary appendix.

Table 1
Calibration and data.

Calibration	
Simulation interval	10 days
Discount rate	$\beta = 0.9987$ (1.2% quarterly return)
Preferences	CRRA: log (benchmark), $\dfrac{c^{1-\gamma}}{1-\gamma}$
Separation rate	$\delta = 0.1/9 \approx 0.01$
Matching function	$\mu(\theta) = 0.15\theta^{0.28}$
Vacancy cost	k set s.t. steady-state job-finding rate consistent with data
Productivity	$z = [1-\Delta z, 1, 1+\Delta z]'$, with mean one, transition matrix $\Pi = \lambda \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (1-\lambda) \begin{pmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} \\ 0 & 1 & 0 \end{pmatrix}$ $\Delta z = 0.03115$, $\lambda = 0.98805$ to match measured standard deviation, AR1-coefficient of productivity (after aggregating to quarterly, taking logs, filtering)
Simulations	Model-generated data are aggregated to quarterly, logged, HP(10^5)-filtered. Model-generated moments are averaged over 1000 simulations of 55 year productivity realizations. The initial distribution has full unemployment and the first 400 000 periods thrown away
Data	
Productivity	BLS reported quarterly real output per worker for the non-farm business sector for 1951–2005, taking logs and HP-filtering, gives standard deviation 0.02 and AR1-coefficient 0.89
Wages	BLS reported quarterly compensation and employment for the non-farm business sector for 1951–2005. Wage refers to per worker compensation (no hours choice in model). BLS reports a current dollar compensation index, which is deflated by the CPI for all urban consumers and divided by employment
Vacancies	Conference Board's help-wanted advertising index
Unemployment	Current Population Survey
Filtering	All data are logged and HP(10^5)-filtered

Notes: The calibration seeks consistency with Shimer (2005a) and the subsequent literature. This motivates the calibration of the matching function, separation rate and vacancy cost, as well as choice of filter. The interval is short both to allow using a Cobb–Douglas matching function, common in empirical studies estimating matching functions (to guarantee matching probabilities between zero and one, short enough periods are needed) as well as because unemployed workers are forced to stay unemployed for at least one period in the model. The elasticity of the matching function $\alpha = 0.72$ is based on estimates from time series data on vacancies and unemployment, and the separation rate on unemployment data. (Robustness checks show that the results hold also for lower values of the matching function elasticity.) As in Shimer (2005a), the steady-state θ can normalized to be one (the calibration involves a normalization because the units of vacancies are not pinned down). The vacancy cost is calibrated such that the average job-finding probability equals the empirically observed 0.15 per period. Doing so guarantees that the model will be consistent with the average level of unemployment in all the results presented. The transition matrix is chosen such that conditional on an aggregate shock, if productivity is intermediate it is equally likely to increase or decrease, and if it is high or low it will return to the intermediate value.

4.1. Calibration

The calibration is described in Table 1. It follows largely Shimer (2005a) and the related literature for comparability. However, to avoid taking a stand on the value of unemployment consumption, b, I present results for a range of values, so that the reader can see the sensitivity to this much stressed variable. The value of unemployment consumption is important for the amplification properties of the model, but the literature remains divided on its appropriate calibration.[11] For direct evidence on b, note that the model's workers are excluded from asset markets and consume their income each period, so b corresponds roughly to the consumption of the unemployed relative to that of the employed, because the wage level is close to one. Empirical estimates of how much consumption falls upon entering unemployment range from 5% to 14% .[12]

The computation strategy used to solve the model in the case of two-sided limited commitment requires restricting the productivity states z to a relatively small set. The baseline calibration uses a three state process for productivity. Because the degree of discretization may matter for the impact of limited commitment in contracting, a supplementary online

[11] While Shimer (2005a) calibrates the parameter to the replacement rate of unemployment insurance, roughly 0.4, which implies little amplification, Hagedorn and Manovskii (2008) have argued that the high observed volatility of unemployment is an indication that workers are relatively indifferent with respect to unemployment, and so the appropriate value for the parameter is instead close to one (productivity of market work). A consensus view has not emerged, beyond the suggestion that some intermediate value may be appropriate.

[12] Due to data limitations, empirical estimates are available mainly for food consumption: Aguiar and Hurst (2005) find a 5% drop in food consumption, Gruber (1997) and Stephens (2001), respectively, 7% and 10% drops in food expenditures. As the demand for food is likely to be less elastic than that for other goods, one would expect the total consumption of goods to drop more than that of food. Appropriately, Browning and Crossley (2001) find a 14% drop in a wider measure of consumption expenditures.

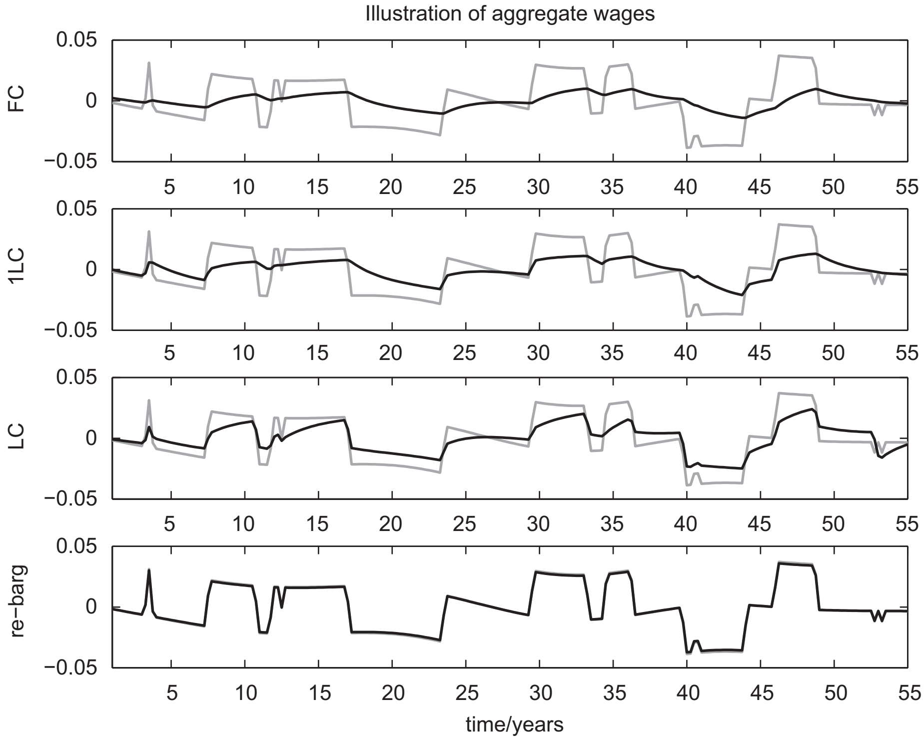

Fig. 1. An illustration of the aggregate wage across contracting environments. *Notes*: The figure shows how model-generated wage data differ across contracting environments: full commitment (FC), one-sided limited commitment where only firms commit (1LC), two-sided limited commitment (LC) and continual re-bargaining of wages. The gray line indicates the underlying productivity realization, with a 1% deviation corresponding to 0.01. The data are aggregated to quarterly, logged and filtered.

appendix provides robustness checks related to the productivity specification: extending to a four state process does not change results in a significant way. Robustness to the estimation errors involved in calculating the moments of the productivity process is also examined.

The next section examines how the model compares to data in terms of the cyclical behavior of the aggregate wage and the vacancy–unemployment ratio, the key variable behind variation in unemployment in the model. The central question is whether the magnitudes of the responses of these variables to productivity shocks in the model are consistent with those in the data. To address the question, it seems appropriate to deviate from the majority of the literature examining the unemployment volatility puzzle, which focuses on the ability of the model to generate the same standard deviation for the vacancy–unemployment ratio as observed in the data. Over the 1951–2005 period, the empirical correlation of the vacancy–unemployment ratio with productivity is only 0.4, while in the model with one shock the correlation is approximately one. The low correlation suggests that there may be other shocks causing variation in the data beyond those affecting productivity, and if these are excluded from the model, then the model should only be expected to explain part of the variation. I therefore measure responses instead as regression coefficients of the vacancy–unemployment ratio and the aggregate wage on productivity (all in logs). The main impact of the regression approach is to adjust both empirical targets down, according to the correlations. These elasticities are denoted as $P(\theta|z), P(w|z)$ and the empirical values are 7.58 and 0.55, respectively.[13]

4.2. The impact of commitment on the aggregate wage

Enriching the Mortensen–Pissarides model with long-term contracting allows it to reproduce observed patterns in the cyclical behavior of individual level wages. The model reproduces the empirical finding that the wages of newly hired workers are more cyclical than those of existing workers (Bils, 1985, and others). It allows aggregate conditions at the time of hiring to have a persistent effect on a worker's wage and, in the case of limited-commitment contracts, it allows the most

[13] $P(x|z) = cov(x,z)/var(z)$ for $x = \theta, w$. The regression measure is used here because it seems a more appropriate measure to use, but the choice does not matter for the main conclusions of the paper, and the interested reader will find the corresponding results using standard deviations in a supplementary online appendix on robustness.

extreme aggregate conditions that have prevailed during the life of a contract to affect this wage as well (Beaudry and DiNardo, 1991; McDonald and Worswick, 1999; Grant, 2003; Macis, 2007). The next sections show that a quantitative evaluation of the model relating it to aggregate wage data supports the two-sided limited-commitment model: it is consistent with observed wage cyclicality, as well as the timing of wage responses to productivity shocks.

Fig. 1 illustrates how the time series of the aggregate wage look in the three different contracting environments. In the full-commitment economy contract wages are constant, with higher productivity at the time of hiring translating into a higher wage level. The aggregate wage is procyclical because of turnover in the labor force. When workers have limited commitment, contract wages remain constant whenever possible, but if the workers' outside option begins to bind when productivity improves, they adjust up together with productivity. Hence also the aggregate wage can jump up in the event of a sufficiently large positive productivity shock, reflecting the adjustment in the contract wages of those workers for whom the outside option binds. When both parties have limited commitment, contract wages will also adjust down if the firms' outside option begins to bind when productivity falls. Hence also the aggregate wage can jump down in the event of a sufficiently large negative productivity shock. The final time series in the figure corresponds the standard wage setting mechanism used in the search and matching literature—continual re-bargaining (see e.g. Pissarides, 1985). These wages result from the bargaining environment of Proposition 6, when the feasible set of contracts is restricted to reflect re-bargaining each period. In that case all workers receive the same wage, and that wage is strongly affected by current productivity.

One way in which the environments differ is how quickly the aggregate wage responds to productivity shocks. To compare the models to data on this dimension, Fig. 2 plots empirical and model-generated correlations of the aggregate wage with lagged productivity. The data show a fairly contemporaneous relationship, with slightly more weight on lags. The fixed wage economy has a notable lag in the correlation because the aggregate wage responds only through turnover in the labor force. The continually re-bargained wage represents the opposite extreme with a sharp contemporaneous correlation. The limited-commitment economies, particularly the two-sided limited-commitment economy, come closer to the empirical counterpart by combining the lagged response through turnover with contemporaneous pro-cyclical adjustments in contract wages.

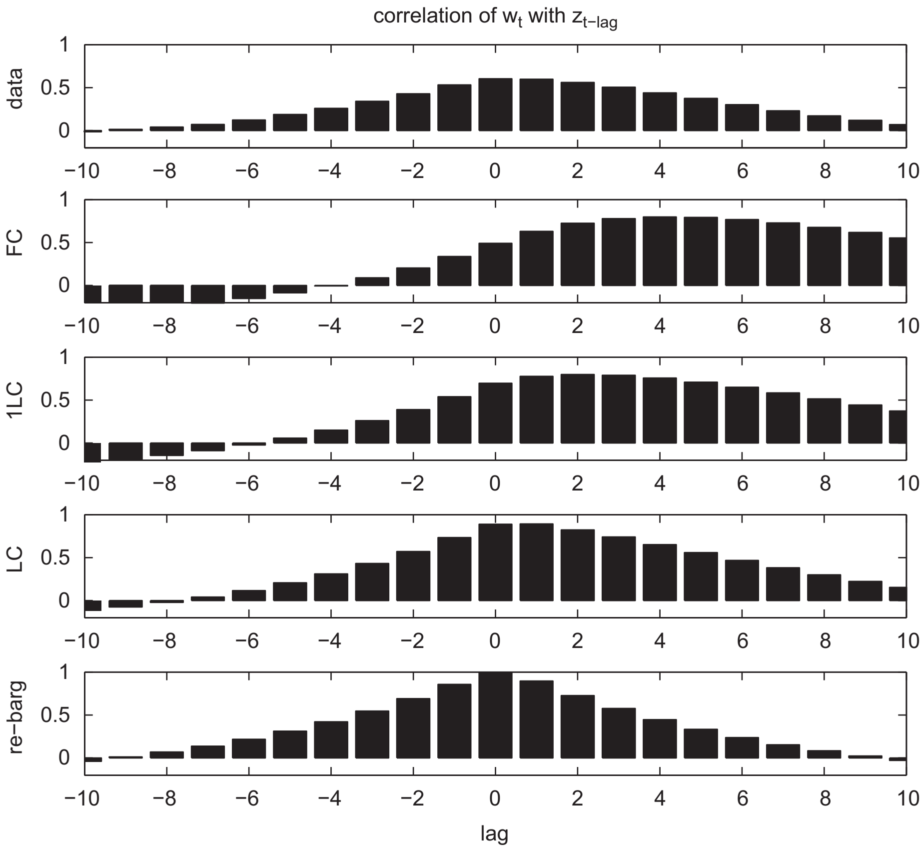

Fig. 2. Correlation of the aggregate wage with lagged productivity. *Notes*: The figure compares correlations of the aggregate wage with lagged productivity in the data versus the different contracting environments: full commitment (FC), one-sided limited commitment where only firms commit (1LC), two-sided limited commitment (LC) and continual re-bargaining of wages.

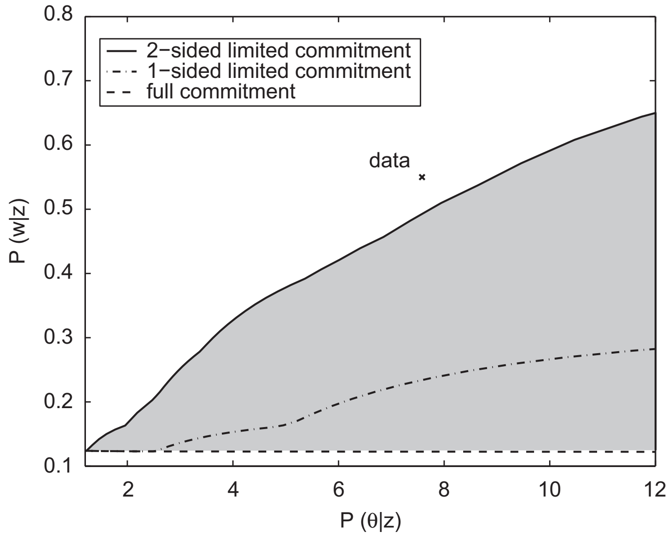

Fig. 3. Sensitivity of vacancy–unemployment ratio θ, aggregate wage w to productivity z. *Notes*: Sensitivities are measured as regression coefficients and denoted by $P(\theta|z)$ and $P(w|z)$. The curves in the figure are traced out by varying b, the level of consumption of unemployed agents, in three contracting environments: full commitment, one-sided limited commitment, and two-sided limited commitment. The calibration of the vacancy cost k guarantees that the level of unemployment is constant in the figure.

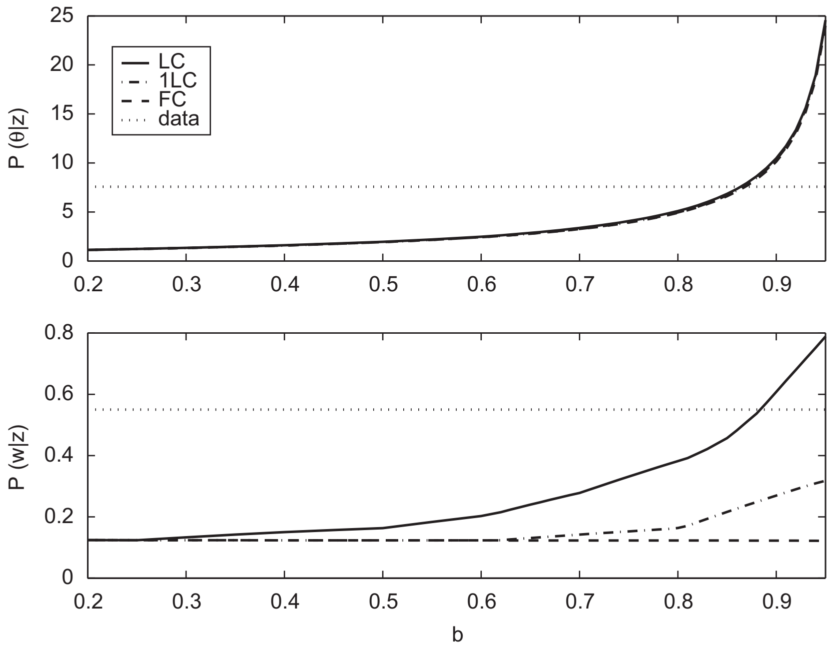

Fig. 4. Sensitivity of vacancy–unemployment ratio θ, aggregate wage w to productivity z. *Notes*: Sensitivities are measured as regression coefficients and denoted by $P(\theta|z)$ and $P(w|z)$. The calibration of the vacancy cost k guarantees that the level of unemployment is constant in the figure. The kinks in the wage plot are due to the finite number of states in the productivity process.

4.3. The volatility of the aggregate wage versus unemployment

Fig. 3 examines how the quantitative performance of the model compares to data in terms of matching the business cycle volatility of the aggregate wage and vacancy–unemployment ratio. It traces out the model produced volatilities for each of the three contracting environments as a function of b, the consumption of the unemployed. The figure shows that the model framework is capable of producing very rigid wages compared to data. Note that the model is able to approximate the empirical level of wage volatility only when wage smoothing is restricted by limited commitment on *both sides*. The figure also makes the important point that the same extent of unemployment cyclicality can well be consistent

Table 2
Impact of risk aversion.

Utility function	Wage setting	b	k	$P(w_t\|z_t)$
	data			0.55
Linear	FC	0.87	0.04	0.12
	1LC	0.87	0.04	0.24
	LC	0.87	0.04	0.53
	Re-barg.	0.87	0.04	0.96
$\gamma = 1$	FC	0.87	0.05	0.12
	1LC	0.87	0.05	0.23
	LC	0.86	0.05	0.49
$\gamma = 5$	FC	0.86	0.07	0.12
	1LC	0.86	0.07	0.17
	LC	0.85	0.08	0.36

Notes: Each row presents the values of the unemployment consumption b and vacancy cost k, which allow the model to match both the level of unemployment and volatility of market tightness observed, given the contracting environment. The lower is the value of b required, the more amplification is produced by the contracting environment itself. Vacancy cost k is s.t. $E\mu = 0.15$ and unemployment consumption b is s.t. $P(\theta_t|z_t) = 7.583$. Preferences are $u(c) = c^{1-\gamma}/(1-\gamma)$ for $\gamma = 0, 1, 5$. When preferences are linear, the form of the optimal contract is not determined. The table presents four alternatives for wage determination in this case, corresponding to the form of the FC, 1LC, LC contracts, as well as continual re-bargaining of wages. The contract form does not affect the values of b, k in this case, but only the cyclicality of the aggregate wage.

with a range of different degrees of wage cyclicality. Observations on the cyclicality of the aggregate wage are not informative about unemployment.

To understand what underlies this crucial figure, Fig. 4 divides it in two parts, allowing the reader to fix a calibration of b and examine the impact of the contracting environment. It is well known that in the standard Mortensen–Pissarides model the cyclicality of the vacancy–unemployment ratio increases in the value of b, and the same holds here as well. A high b implies that workers are relatively indifferent between market work and unemployment, causing productivity shocks of a given size to induce larger changes in hiring. Under limited-commitment contracting, also the cyclicality of the aggregate wage is increasing in b, because participation constraints bind more often when workers are more indifferent.

The figure shows that limited-commitment constraints increase the volatility of both the aggregate wage and unemployment. This seemingly surprising finding is due to the fact that while limited commitment increases the cyclicality of contract wages, as well as starting wages, which translates into increased cyclicality in the aggregate wage, it creates rigidity in the present value of wages used to attract new workers, increasing the cyclicality of vacancy creation. The figure also shows that while the impact on the wage is substantial, the impact on unemployment is relatively modest. The aggregate wage reflects strongly the form of wage contracts, while the impact on the present value of wages is modest.

4.4. *Effects of risk aversion*

The workers' preference for consumption smoothing plays a central role in the model. In fact, if workers have linear preferences, $\gamma = 0$, the model can be shown to reproduce the employment dynamics of the standard Mortensen–Pissarides model.[14] Qualitatively, one would expect two effects from increased risk aversion: on the one hand, the distortions due to the incomplete markets environment become amplified, which implies greater cyclical variation in unemployment and reduced variation in the present value of wages used to attract new workers. On the other hand, participation constraints become less binding, which reduces the impact of limited commitment. When risk aversion is sufficiently high, participation constraints cease to bind completely, making the limited-commitment economies identical to the full-commitment economy, with a very rigid aggregate wage.

Table 2 examines the quantitative impact of increasing γ. For each value of γ and each contracting environment, it shows how high a value of b is needed to match the observed volatility of θ. The lower the value is, the more amplification is due to the environment itself. To guarantee that the level of unemployment remains fixed in these comparisons, as in the previous figures, the vacancy cost adjusts.[15] The table shows that increasing risk aversion increases the volatility of the vacancy–unemployment ratio, especially when limited commitment binds, but that the impact is relatively modest in magnitude. At the same time, the impact on the cyclicality of the aggregate wage is quite substantial. Wage volatility falls

[14] When the bargaining power of workers satisfies the Hosios-condition, as often imposed.

[15] Matching both the level and the volatility determines the two parameters b and k uniquely, because while both b and k increase the level of unemployment, they have opposing effects on volatility.

both because the limited-commitment economies become more similar to the full-commitment economy, and because the present value of wages used to attract new workers becomes more rigid. In a full-commitment economy the latter is accomplished through reduced differences in the wage levels of workers hired in booms versus recessions, which also makes the aggregate wage more rigid.

These findings reinforce the conclusions that: (i) the model is capable of producing a very rigid aggregate wage, without the substantial increase in the cyclical volatility of unemployment seen with exogenous wage rigidity, and (ii) a given level of unemployment volatility can be consistent with a range of wage volatilities, depending on the environment.

5. Conclusions

The aggregate wage is not informative about the measure of wage rigidity relevant for understanding unemployment fluctuations: how much the present value of wages used to attract new workers varies over the cycle. In an ideal world, one could estimate these present values for individual workers directly, using a sufficiently wide and long panel data set with information on tenure, and compare them for workers hired in booms versus recessions. With limitations on data, a more practical approach is to make assumptions about the type of contract governing the evolution of individual wages in the data, and take advantage of that structure to calculate estimates of these present values. Kudlyak (2007) conducts such an exercise, failing to find evidence of significant rigidity in wages. In related work, Haefke et al. (2007) and Pissarides (2007) interpret the higher cyclical volatility of starting wages, as compared to that of the aggregate wage, as evidence against wage rigidity. Creating the link between the starting wage and the present value requires assumptions about how wages evolve in contracts, and how informative the results are hinges on how accurate those assumptions are. Here the limited-commitment contracting framework has the advantage of supporting empirical literature.[16]

This paper is not the first to look for micro-foundations for wage rigidity, as called for by Hall (2005). Gertler and Trigari (2008) introduce staggered wage bargaining into the Mortensen–Pissarides model, allowing only a subset of firms to adjust their wages each period. In their model hiring decisions are distorted in those firms that are constrained to keep wages fixed. Hall and Milgrom (2008) argue that the threat points in the bargaining problem faced by workers and firms in the Mortensen–Pissarides model are misspecified. Altering these threat points to reflect the delay of negotiations rather than the ending of negotiations creates some added rigidity in the present value of wages. Several authors have also explored the role of informational asymmetries and incomplete markets for creating wage rigidities, interesting approaches which are non-trivial to incorporate into quantitative macroeconomic analysis.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jmoneco.2008.12.009.

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[16] For a survey see Thomas and Worrall (2007).

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