Hours and Employment Over the Business Cycle: A Bayesian Approach*

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Abstract

We show that an estimated business cycle model with search-and-matching frictions and a neoclassical hours-supply decision cannot account for the cyclical behavior of U.S. hours and employment and their comovement with macroeconomic variables. A parsimonious set of features reconciles the model with the data: non-separable preferences with parametrized wealth effects and costly hours adjustment. The model, estimated with Bayesian methods, offers a structural explanation for the observation that in post-war U.S. recoveries, the covariance between the labor margins is either positive or negative. The contribution of hours per worker to total hours is quantitatively significant, with a notable component stemming from its indirect effect on employment adjustment.

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1 Introduction

A vast literature addresses the cyclical behavior of the labor market in the context of the Mortensen-Pissarides search and matching model (Mortensen and Pissarides, 1994, and Pissarides, 2000), arguably the benchmark theory of equilibrium unemployment today.[1] Nevertheless, the majority of this literature ignores the distinction between changes in average hours per worker (the intensive margin) versus movements in and out of employment (the extensive margin).[2] Omitting the compositional adjustment of total hours worked is not without loss of generality. Changes in hours per worker are about as large as changes in employment in many OECD countries (Ohanian and Raffo, 2012). In the U.S., the volatility of the intensive margin accounts for approximately one-third of the unconditional variability of aggregate hours. Moreover, in specific U.S. business cycle episodes, the two margins covary either positively or negatively, and their relative contribution to aggregate fluctuations is time-varying.[3]

In this paper, we take up the challenge of accounting for and explaining the cyclical behavior of the margins of labor adjustment and their comovement with the rest of the economy. These relations are central for policy prescriptions and welfare analysis from quantitative business-cycle models, as labor market responses shape the dynamics of key policy variables like the output gap. We first determine under which conditions a business cycle model that features search-and-matching frictions can account for macro data that include both margins of labor adjustment. We then provide a structural assessment of the contribution of the intensive margin to aggregate fluctuations, shedding new light on the sources of labor market dynamics.

Our baseline specification utilizes a state-of-the-art business cycle model that successfully accounts for key macroeconomic time-series, as shown in Christiano et al. (2005), Smets and Wouters (2007), and Justiniano et al. (2010).[4] We embed a labor market structure that follows the conventional approach in search and matching models that include the intensive margin—see Andolfatto (1996), Arseneau and Chugh (2008), Christiano et al. (2011), Ravenna and Walsh (2012), and Trigari (2009), to name a few.[5] Firms adjust labor inputs either by posting vacancies or changing

[1]See, among others, Andolfatto (1996), den Haan et al. (2000), Gertler and Trigari (2009), and Shimer (2005).

[2]Some early contributions, including Cho and Cooley (1994), Kydland and Prescott (1991), and Hansen and Sargent (1988), calibrate models in which the supply of total hours adjust along both the intensive and extensive margins, but abstract from search and matching frictions.

[3]Section 2 discusses the data and robustness of these computations. In addition, we document that the positive covariance between hours per worker and employment is a significant contributor to total hours variation.

[4]The model features habit formation, investment adjustment costs, variable capital utilization, and nominal price and wage rigidities.

[5]These studies do not assess the ability of the search and matching model to account for the cyclicality of the

the number of hours per worker. Households face a standard neoclassical hours-supply decision, which also is consistent with the business cycle literature. In equilibrium, hours per worker adjust to equate the marginal rate of substitution between hours and consumption to the value of the marginal product of hours. The widespread preference for this setup stems from its invariance to the Barro (1977) critique, since wages do not have a direct impact on on-going worker-employer relations (and thus on the adjustment of hours per worker).[6]

We estimate the model using Bayesian inference with U.S. data.[7] Our full information approach provides an ideal laboratory to study the empirical performance of the model, since it allows us to evaluate the model fit relative to a large set of macro moments, beyond pure labor market outcomes. Moreover, it allows us to encompass most of the views on the sources of business cycles found in the literature, giving disturbances other than the neutral technology shock a fair chance of accounting for labor market adjustments.

Our analysis yields three main results. First, the baseline model cannot account for the cyclicality of the margins of labor adjustment. In particular, the model cannot reproduce the positive unconditional covariance between employment and hours per worker, and it generates counterfactual volatilities for both labor margins. The model also cannot account for the covariance between both labor margins and macroeconomic times series; namely it generates counterfactually low (high) comovement of hours per worker (employment) with aggregate output and consumption. The main issue is that the model implies a countercyclical behavior of hours per worker conditional on both technology and demand shocks, a result contrary to existing VAR evidence—see for instance, Ravn and Simonelli (2007). Moreover, the intensive margin's relative volatility is counterfactually high in the presence of hours supply shocks.

Our second contribution is to reconcile the model with the data. Two candidate explanations for the counterfactual labor market dynamics are the strength of short-run wealth effects on labor supply, which affects the response of hours per worker to TFP and demand shocks, and the asymmetric costs of adjusting the two labor margins, since posting vacancies is costly, while hours per worker are frictionless. For these reasons, we introduce additional flexibility in the model by

labor margins, nor do they address the contribution of fluctuations in hours per worker to labor market and aggregate dynamics.

[6]Two alternative determinations of hours per worker occasionally considered in the literature are right-to-manage and joint Nash bargaining over wages and hours per worker—Nash bargaining implies that hours per worker no longer satisfy the standard neoclassical condition in the presence of wage rigidities. Both setups are not immune to Barro's critique. We explore the fit of these alternative setups, finding that the performance of both models is inferior to the baseline specification.

[7]To avoid the effective lower bound on monetary policy, we exclude the Great Recession for estimation.

including two ancillary features: non-separable preferences that feature parametrized wealth effects on labor supply as in Jaimovich and Rebelo (2009) and costly hours' adjustment.[8,9] We re-estimate the model and find strong support in favor of weak short-run wealth effects and positive hours adjustment costs. Intuitively, weakening the wealth effect eliminates the negative comovement between hours per worker and employment and increases the comovement of hours per worker with both output and investment. The presence of costly hours' adjustment prevents excessive variability in hours per worker, the second key dimension for reproducing the cyclical behavior of both margins of labor adjustment.

Finally, we examine the behavior of hours and employment in post-WWII U.S. recessions and recoveries, as there has been revitalized interest in labor-market dynamics in the wake of the Great Recession. The estimated model offers a structural interpretation for the observed time-varying comovement between hours per worker and employment in these periods. Hours and employment comove positively in response to demand and supply shocks, and comove negatively in response to labor-market shocks—shocks that affect the rigidity of real wages and hours supply. Moreover, a model counterfactual shows that adjustment in hours per worker had sizable effects on the recovery of total hours (up to 3.5 percentage points). A notable component stems from the indirect effect of hours per worker on employment (beyond the direct effect of hours per worker on total hours): the intensive-margin adjustment increases employment losses during recessions and delays employment recoveries.

To understand the indirect effect of hours per worker on employment, we examine the aggregate dynamics when hours per worker are constant. With the intensive margin fixed, the expected present discounted value of new matches varies less in response to shocks that induce positive comovement between the margins of labor. Accordingly, firms adjust effective capital more than employment, holding all else constant. Lack of adjustment in the intensive margin also implies that firms can no longer substitute away from the relatively cheaper labor input in response to shocks that induce a negative comovement between the margins of labor. As a result, both effects imply that fluctuations in hours per worker increase the response of employment to aggregate shocks.

[8]The preference specification in Jaimovich and Rebelo (2009) allows us to study the limiting case of no wealth effects considered by Greenwood et al. (1988), while preserving the existence of balanced growth in the model. Imbens et al. (1999) provide microeconomic evidence of weak short-run wealth effects.

[9]In the data, hours adjustment is constrained both by the regulation of working time, as well as technological frictions. For instance, the "Wages and the Fair Labor Standards Act" establishes that covered nonexempt employees in both private and public sectors must receive overtime pay at one-half times the regular rate for hours over 40 per week. Moreover, the incidence of flexible work hours varies by occupation (Beers, 2000); it is lower for jobs that dictate set intervals for work (e.g., nurses, firefighters, pilots) and most common among workers in executive, administrative, sales and managerial occupations. Other technological constraints include set-up costs and coordination issues.

We consider several robustness exercises that support our results. Issues with the baseline model hold regardless of the number of labor-market observables included in the estimation—either total hours alone or hours and employment together—and the shocks that affect labor adjustment.[10] Issues hold also regardless of the data-measure for labor-market variables and wages. In addition, the counterfactual behavior of the baseline model is not intrinsically linked to a specific value of the Frisch elasticity of labor supply.[11]

While we estimate the model on U.S. data, the results of our paper are broader in scope. First, as documented by Ohanian and Raffo (2012), hours and employment positively comove in several economies (for instance, in the U.K., Canada, and Japan), suggesting that the inability of the baseline model to account for the margins of labor adjustment is not limited to the U.S. economy. Second, parametrized wealth effects and costly hours' adjustment introduce enough flexibility to allow the model to match a broad array of empirical regularities about hours per worker and employment, including potentially negative ones observed in some European economies.

This paper relates to several strands of the literature. First, since Shimer (2005), a large literature addresses the ability of the search and matching model to replicate the cyclical behavior of vacancies and employment. While the debate has for the most part focused on calibrated versions of the search model, a few recent contributions examine the issue in the context of quantitative, estimated models (Christiano et al., 2016, Gertler et al., 2008, and Justiniano and Michelacci, 2012).[12] In contrast, we document the inability of the model to jointly reproduce the cyclical behavior of hours per worker, employment, and their empirical covariances with macroeconomic time series.

This paper also relates to the literature addressing the behavior of employment in U.S. cyclical recoveries. In particular, an active strand of research addresses the so-called "jobless recoveries" following the past three U.S. recessions (of 1991, 2001, and 2009), where aggregate employment continued to decline for years following the turning point in aggregate income and output.[13] Our

[10] When we estimate using aggregate hours as the only labor market observable, we either consider a standard bargaining power shock or a shock that affects the hours margin. When we include hours and employment as observables, we consider simultaneously the bargaining power shock and a hours supply shock.

[11] While our estimates for this elasticity are aligned with microeconometric evidence, the inability of the model to reproduce the margins of labor adjustment persists even when we calibrate the Frisch elasticity to values used in the macroeconomic literature, as such values counterfactually augment the intensive margin's variability.

[12] Christiano et al. (2011) estimate a small-open economy model featuring search and matching frictions and endogenous hours per worker. They focus on the role of shocks and frictions for business cycle dynamics, without addressing the model's capability to capture the margins of labor adjusmtnet. Altug et al. (2011) show that financial frictions contribute to the dynamics of employment and hours per worker in a small-open economy model calibrated to match features of emerging economies. Balleer et al. (2016) identify, quantify, and interpret the dynamics of short-time work (i.e., publicly subsidized work time reductions) in Germany.

[13] No consensus has yet emerged regarding the source of jobless recoveries. Some attribute the occurrence of this

results provide additional insights to the debate by emphasizing the role of hours' adjustment for employment dynamics during these episodes.

The rest of the paper is organized as follows. Section 2 reviews the empirical relation of U.S. hours and employment. Section 3 outlines the model. Section 4 describes the approach for inference and discusses the cyclical behavior of the margins of labor adjustment in the estimated baseline model. Section 5 studies the performance of the alternative model featuring parameterized wealth effects and hours adjustment costs. Section 6 discusses the cyclical behavior of hours per worker and employment in post-war U.S. recoveries. Section 7 evaluates the robustness of the results to alternative model specifications. Section 8 concludes.

2 Hours and Employment in the Data

We begin with a review of stylized facts about U.S. hours per worker, employment, and total hours worked. In contrast to previous work, we use measures of total hours worked and employment for the entire economy constructed by the BLS from the Current Employment Statistics (CES) survey.[14] Francis and Ramey (2009) show this economy-wide total hours series is less sensitive to sectoral shifts than nonfarm business sector measures. First, we find the covariance of hours per worker and total hours can account for up to 30 percent of the unconditional variation in total hours. Second, hours per worker and employment positively co-move. The positive covariance of the intensive and extensive margins is a substantial contributor to the variability of total hours ($20-30\%$), on top of the direct share of hours per worker's variance (10-18%). Third, both the comovement and the relative contribution of the intensive margin varies in specific business cycle episodes. We illustrate this by showing time-variation in the intensive margin's contribution to recessions and recoveries. We also highlight the robustness of these facts across alternative labor data sets and discuss their importance for explaining fluctuations in aggregate hours.

We use quarterly data over the period 1965:1-2007:4, which corresponds to the estimation sample period in section 4.[15] Hours per worker is constructed from the total hours and employment series.

phenomenon to fundamental changes in the underlying economic structure (e.g., Schreft et al., 2005 and Groshen and Potter, 2003). Others focus on cyclical explanations, such as the intensive margin of labor adjustment in the wake of a short and shallow recession (Bachmann, 2012). Jaimovich and Siu (2012) show that jobless recoveries in the aggregate are accounted for by jobless recoveries in the middle-skill occupations that are disappearing because of job polarization. Gali et al. (2012) study slower recoveries in an estimated model that abstracts from endogenous fluctuations in hours per worker.

[14] This data is publicly available from the BLS website at www.bls.gov/lpc/special_requests/us_total_hrs_emp.xlsx. To construct a total economy series, the Current Employment Statistics data is supplemented from other sources. See the BLS website for details.

[15] Results are similar using a longer data sample from 1965:1-2014:4, as documented in appendix A.

Total hours and employment are divided by the civilian non-institutional population to express in per capita terms. All variables are expressed in logs and multiplied by 100. Over the sample period, employment exhibits an upward trend while hours per worker exhibits a downward trend.[16] We consider several alternative detrending methods. Our preferred method removes a linear trend from each series, which corresponds to the series used for estimation in section 4. When hours and employment are linearly detrended, their sum almost perfectly matches the original, demeaned total hours series (their correlation is over 0.99). Thus, the linear filtering appears to account for the low-frequency structural features of employment and hours per worker while preserving the original properties of the total hours series. In addition, we apply a HP filter with smoothing parameters of 1600 and 10^5 and a band pass filter as in Christiano and Fitzgerald (2003).

To assess the contribution of the intensive margin to labor adjustment, we consider two standard decompositions of the variance of total hours. The first decomposition exploits the fact that

$$\text{var}(TH_t) = \text{cov}(TH_t, h_t) + \text{cov}(TH_t, L_t),$$

where TH_t is total hours worked, h_t is hours per worker, and L_t is employment. Using this decomposition, we compute the shares of the variance attributed to hours per worker and employment as

$$\beta_{cov,h} \equiv \frac{\text{cov}(TH_t, h_t)}{\text{var}(TH_t)}, \quad \beta_{cov,L} \equiv \frac{\text{cov}(TH_t, L_t)}{\text{var}(TH_t)}.$$

In addition, we consider the following alternative decomposition:

$$\text{var}(TH_t) = \text{var}(h_t) + \text{var}(L_t) + 2\text{cov}(h_t, L_t),$$

and define the shares of the variance attributed to hours per worker, employment, and the covariance term respectively as

$$\beta_h \equiv \frac{\text{var}(h_t)}{\text{var}(TH_t)}, \quad \beta_L \equiv \frac{\text{var}(L_t)}{\text{var}(TH_t)}, \quad \beta_{cov} \equiv \frac{2\text{cov}(h_t, L_t)}{\text{var}(TH_t)}.$$

Table 1 displays these variance shares for the alternative detrending methods. While em-

[16] As shown by Kirkland (2000), the decline in average hours per worker recorded by the CES survey can be attributed to the disproportionate increase of nonsupervisory workers in retail trade and services—the two industry divisions in the service-producing sector with the lowest average weekly hours—together with the decline in the percentage of production workers in mining and manufacturing—the two divisions with the highest number of average weekly hours. See also Wolters (2016) for a discussion of low-frequency movements in hours per worker.

ployment accounts for the largest share of variation in total hours, the intensive margin plays a quantitatively significant role. The first decomposition shows that the covariance between hours per worker and total hours ($\beta_{cov,h}$) accounts for up to one-third of the total variation in TH_t. The second decomposition shows that the positive covariance between hours and employment (β_{cov}) explains approximately one-third of the variability in total hours. Thus, fluctuations in the intensive margin affect total hours both directly and indirectly through employment.

Table 1: Decomposition of Total Hours and Labor Market Comovement

Filtering	$\left(\frac{\text{cov}(TH_t,h_t)}{\text{var}(TH_t)}\right)$	$\left(\frac{\text{cov}(TH_t,L_t)}{\text{var}(TH_t)}\right)$	$\left(\frac{\text{var}(h_t)}{\text{var}(TH_t)}\right)$	$\left(\frac{\text{var}(L_t)}{\text{var}(TH_t)}\right)$	$\left(\frac{2\text{cov}(h_t,L_t)}{\text{var}(TH_t)}\right)$
Linear	0.33	0.67	0.18	0.51	0.31
HP 1600	0.21	0.79	0.10	0.67	0.23
HP 10^5	0.25	0.75	0.10	0.60	0.30
BP	0.23	0.77	0.10	0.63	0.27

Appendix A documents the robustness of these results to two alternative data sources. The first uses labor variables from the Current Population Survey (CPS) which are augmented with armed forces data to provide an alternative economy-wide measure, as in Ramey (2012). CPS total hours data exhibit less pronounced low-frequency variation than CES measures, as shown by Frazis and Stewart (2010). Our results are robust to unfiltered and filtered measures of these variables. In addition, the results remain when using the labor market variables of Smets and Wouters (2007), which are widely employed in the DSGE estimation literature. In this case, hours per worker can contribute approximately 50 percent of the variation in total hours.

While Table 1 documents an unconditional positive correlation between hours per worker and employment, the comovement varies in specific episodes. To illustrate this, the bottom panel of figure 1 plots total hours, employment, and hours per worker during five recession-recovery episodes: 1970:1, 1975:1, 1982:4, 1991:1, and 2001:4.[17] For reference, the figure displays the first difference of the natural logarithm of GDP as well (top panel). We display employment and hours per worker relative to their linear trends. Hours per worker and employment positively co-move in some recoveries, such as 1982:4, but negatively co-move in other episodes, as in 1991:1. In addition, hours per worker is quantitatively important for aggregate hours in several recoveries. For instance, at the 1982:4 trough, the difference in employment and total hours relative to trend was over two

[17] The literature comparing employment measures in jobless recoveries suggests preference for CES data measures similar to those used here. See Bachmann (2012) for a review of the literature.

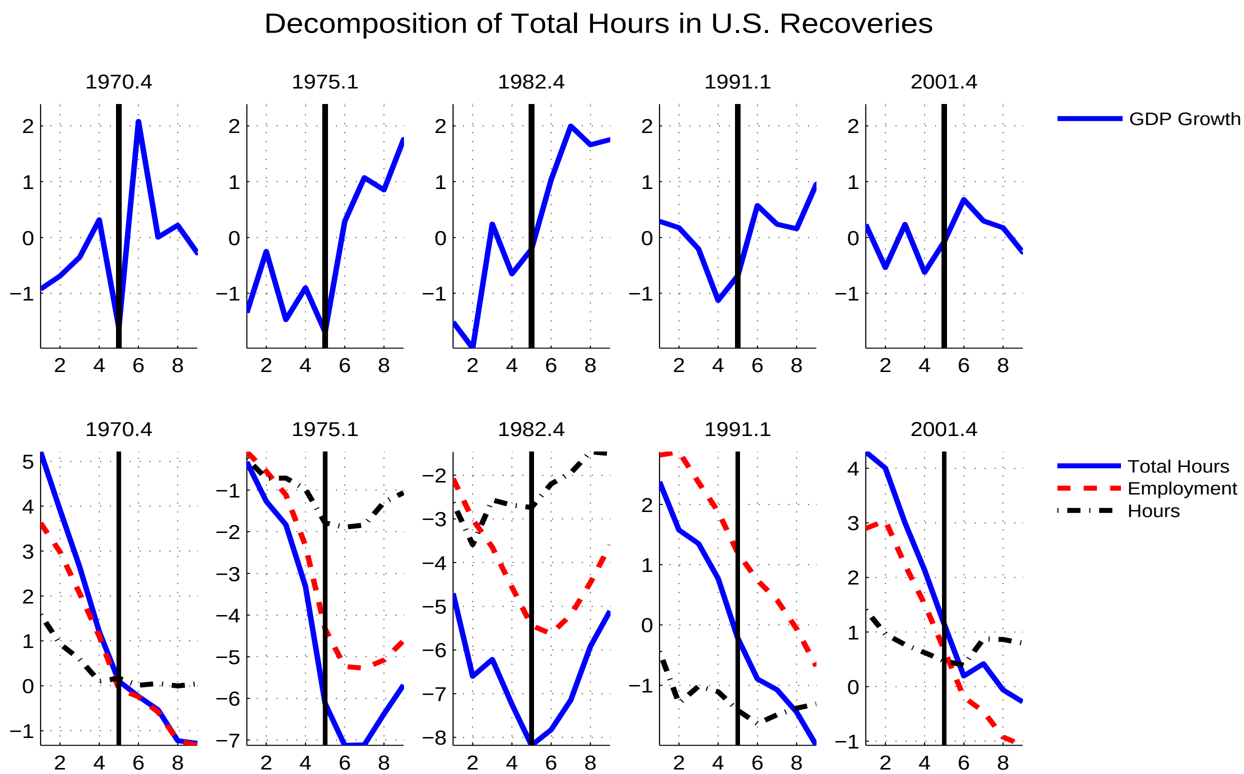

Figure 1. U.S. cyclical recoveries. Solid vertical lines indicate the troughs, using the NBER dates. Labor data are measures for the entire economy.

percentage points, whereas four quarters later the gap shrunk to a difference of about one percentage point (see the bottom row, column three). The closing of the gap was due to hours per worker, which was rising on average over the period. Likewise, in the recovery of 2001:4, total hours and hours per worker exhibited a short increase two periods after GDP's trough, while employment steadily declined over the whole episode. As shown in Appendix A, the time-varying comovement in recession-recovery episodes is robust across different detrending methods and alternative data sources.

In the subsequent sections, we focus on developing a model consistent with these patterns in the data.

3 The Model

This section outlines a medium-scale, dynamic stochastic general equilibrium model that features labor-market search and matching frictions. The model shares salient details that many have found useful for capturing features of the data. These include habit formation, costs of adjusting the flow of investment, variable capital utilization, and nominal price and wage rigidities.

The modeling of the labor market follows closely the existing literature, with two important generalizations. First, we consider a general class of preferences that allow us to parameterize the strength of short-run wealth effects on the labor supply. Second, we introduce costly hours adjustment. The model nests the standard framework analyzed in the literature, absent hours adjustment costs and with household's preferences restricted to be additively separable.

Finally, we abstract from monetary frictions that would motivate a demand for currency and model a cashless economy following Woodford (2003). Below, variables without a time subscript denote non-stochastic values along the balanced growth path.

Household Preferences

The economy is populated by a representative household with a continuum of members along the unit interval. In equilibrium, some family members are unemployed, while others are employed. As is common in the literature, we assume that family members perfectly insure each other against variation in labor income due to changes in employment status, so that there is no *ex post* heterogeneity across individuals in the household (see Andolfatto, 1996, and Merz, 1995).

Household's per-period utility depends on current consumption, C_t, lagged consumption C_{t-1} (due to the presence of habit formation), and the disutility of hours supplied by employed members: $H_t \equiv \bar{h}_t \int_0^{L_t} v\left(h_{jt}\right) dj$, where L_t denotes the mass of employed workers, h_{jt} denotes hours worked by the employed member j, and $v\left(\cdot\right)$ is a convex function. The term $\bar{h}_t$ denotes an exogenous shock to the marginal disutility of hours worked, which evolves according to $\log \bar{h}_t = \rho_{\bar{h}} \log \bar{h}_{t-1} + \varepsilon_{\bar{h}t}$ with $\varepsilon_{\bar{h}t} \overset{iid}{\sim} N\left(0, \sigma_{\bar{h}}^2\right)$. The representative household maximizes the expected intertemporal utility function

$$W_t \equiv E_t \sum_{s=t}^{\infty} \beta^{s-t} \bar{\beta}_s \left[u\left(C_s, C_{s-1}, H_t\right)\right], \tag{1}$$

where $\beta \in (0,1)$ is the discount factor and $\bar{\beta}_t$ denotes an exogenous shock to the discount factor, which evolves according to $\log \bar{\beta}_t = \rho_{\bar{\beta}} \log \bar{\beta}_{t-1} + \varepsilon_{\bar{\beta}t}$ with $\varepsilon_{\bar{\beta}t} \overset{iid}{\sim} N\left(0, \sigma_{\bar{\beta}}^2\right)$.

As discussed in the next section, we consider two alternative specifications for $u\left(\cdot\right)$: additively separable preferences (the benchmark in the literature), and non-separable preferences with parametrized wealth effects.

The consumption basket C_t aggregates differentiated consumption varieties, $C_{\omega t}$, in Dixit-Stiglitz form: $C_t = \left[\int_0^1 C_{\omega t}^{\left(\bar{\theta}_t - 1\right)/\bar{\theta}_t} d\omega\right]^{\bar{\theta}_t/\left(\bar{\theta}_t - 1\right)}$, where $\bar{\theta}_t > 1$ is the exogenous elasticity of substitution across goods. We assume that $\bar{\theta}_t$ follows the stochastic process $\log \bar{\theta}_t = \rho_{\bar{\theta}} \log \bar{\theta}_{t-1} +$

$(1-\rho_{\bar{\theta}}) \log \bar{\theta} + \varepsilon_{\bar{\theta}t}$, where $\varepsilon_{\bar{\theta}t} \overset{iid}{\sim} N\left(0, \sigma^2_{\bar{\theta}}\right)$, which, following the literature, we refer to as a price markup shock. The corresponding price index is given by: $P_t = \left[\int_0^1 P_{\omega t}^{1-\bar{\theta}} d\omega\right]^{1/\left(1-\bar{\theta}\right)}$, where $P_{\omega t}$ is the price of variety ω.

Production

There are two vertically integrated production sectors. In the upstream sector, perfectly competitive firms use capital and labor to produce a homogenous intermediate input. In the downstream sector, monopolistically competitive firms purchase intermediate inputs and produce the differentiated varieties that are sold to consumers. This production structure is common in the search and matching literature featuring nominal rigidities and monopolistic competition, as it simplifies the introduction of labor market frictions in the model; see, for instance, Gertler et al. (2008), Ravenna and Walsh (2011), and Trigari (2009).

Intermediate Input Producers

There is a unit mass of perfectly competitive intermediate producers. Production requires capital and labor. Within each firm there is a continuum of jobs; each job is executed by one worker. Capital is perfectly mobile across firms and jobs and there is a competitive rental market in capital. All jobs produce with identical exogenous productivity $\bar{A}_t$. We assume that the growth rate of technology, $\bar{g}_{At} \equiv \bar{A}_t/\bar{A}_{t-1}$, follows the stochastic process: $\log \bar{g}_{At} = \rho_{\bar{g}_A} \log \bar{g}_{At-1} + (1-\rho_{\bar{g}_A}) \log \bar{g}_A + \varepsilon_{\bar{g}_A t}$, where $\varepsilon_{\bar{g}_A t} \overset{iid}{\sim} N\left(0, \sigma^2_{\bar{g}_A}\right)$.

A filled job in the representative firm j produces $(k_{jt})^a \left(\bar{A}_t \tilde{h}_{jt}\right)^{1-\alpha}$ units of output, where k_{jt} is the stock of capital allocated to the job and $\tilde{h}_{jt} \equiv h_{jt}\left[1 - \frac{\phi_h}{2}\left(h_{jt} - h_j\right)^2\right]$ denotes hours per worker net of a cost of adjustment $\phi_h \geqslant 0$.[18] The latter adjustment cost captures various frictions that constrain the ability of firms to adjust hours per worker—for instance, technological constraints due to set-up costs and coordination issues. Total producer's output exhibits constant returns to scale in total effective hours and capital:

$$Y_{jt}^I = K_{jt}^{\alpha}\left(\bar{A}_t L_{jt} \tilde{h}_{jt}\right)^{1-\alpha}, \tag{2}$$

where L_{jt} is the measure of jobs within the firm and $K_{jt} \equiv L_{jt} k_{jt}$.[19]

[18] Since all jobs produce with identical aggregate productivity $\bar{A}_t$, all existing matches produce the same amount of output using the same capital and hours inputs. For this reason, we omit a job-specific index.

[19] This stems from the fact that $Y_{jt}^I = L_{jt}\left(k_{jt}\right)^a \left(\bar{A}_t \tilde{h}_{jt}\right)^{1-\alpha} = K_{jt}^{\alpha}\left(\bar{A}_t L_{jt} \tilde{h}_{jt}\right)^{1-\alpha}$.

The relationship between a firm and a worker can be severed for exogenous reasons. We denote by λ the fraction of jobs that are exogenously destroyed in each period.[20] Job creation is subject to matching frictions. To hire a new worker, firms have to post a vacancy, incurring a real cost $\bar{A}_t \kappa_{jt}$, where $\kappa_{jt} \equiv \kappa V_{jt}^{\tau} / (1+\tau)$. This specification implies that total vacancy costs are convex in the number of posted vacancies, V_{jt}, an assumption that is consistent with the evidence in Merz and Yashiv (2007). We let the vacancy cost drift with the level of technology to ensure balanced growth. The probability of finding a worker depends on a constant returns to scale matching technology, which converts aggregate unemployed workers U_t and aggregate vacancies V_t into aggregate matches $M_t = \chi U_t^{\varepsilon} V_t^{1-\varepsilon}$, where $0 < \varepsilon < 1$. Each firm meets unemployed workers at a rate $q_t \equiv M_t / V_t$. Finally, as is common practice in the literature, all separated workers are assumed to reenter the unemployment pool; i.e., we abstract from workers' labor-force participation decisions.[21]

The timing of events in the labor market proceeds as follows. The firm j begins a period with a stock of L_{jt-1} workers, which is immediately reduced by exogenous separations. Then, the firm posts vacancies V_{jt} and selects the total capital stock, K_{jt}.[22] Once the hiring round has been completed, wages and hours per worker are determined, and production occurs.[23] The law of motion of employment is given by:

$$L_{jt} = (1-\lambda) L_{jt-1} + q_t V_{jt}. \tag{3}$$

As in Arseneau and Chugh (2008), we use Rotemberg's (1982) model of a nominal rigidity and assume that firms face a quadratic cost of adjusting the hourly nominal wage rate, w_{jt}^n. We opt for this formulation rather than staggered wage adjustment (as for instance in Gertler et al., 2008), since it ensures the existence of a representative producer in the presence of endogenous hours adjustment and parameterized wealth effects, providing tractability.[24] From a quantitative

[20] Hall (2005) and Shimer (2005) argue that, in the U.S. data, the separation rate varies little over the business cycle, although part of the literature disputes this position; see Davis et al. (1998) and Fujita and Ramey (2009).

[21] See Campolmi and Gnocchi (2016) for a standard New Keynesian model with search and matching frictions that incorporates a participation decision. They show that the participation margin moderately increases the volatility of employment.

[22] With full capital mobility and price-taker firms in the capital market, it is irrelevant whether producers choose the total stock of capital K_{jt}, or, instead, determine the optimal capital stock for each existing job, k_{jt}. Moreover, as noted by Cahuc et al. (2008), the specific timing of the capital decision is immaterial for the equilibrium allocation, since capital can be costlessly adjusted within each firm—firms can always re-optimize K_{jt} within a given a period.

[23] Thus, labor-market matching occurs within a period, which, as noted by Arseneau and Chugh (2012), is empirically descriptive of U.S. labor-market flows at quarterly frequencies.

[24] In general, these alternative sources of wage rigidity are not observationally equivalent, even in a first-order approximation to the model policy functions around a deterministic steady state with zero net inflation. The reason is that, as discussed by Gertler and Trigari (2009), the wage dispersion implied by staggered Nash bargaining generates a spillover effect on the average wage that is absent with convex wage adjustment costs.

perspective, these alternative specifications have second-order effects, since a version of our model that abstracts from fluctuations in hours per worker yields aggregate dynamics that are virtually identical to Gertler et al. (2008).[25]

The real, per-worker cost of changing the nominal wage between period $t-1$ and t is

$$\Gamma_{w_jt} \equiv \frac{\phi^w \bar{A}_t}{2} \left(\frac{w_{jt}^n}{w_{jt-1}^n} \pi_C^{\iota_w - 1} \pi_{Ct-1}^{-\iota_w} - \bar{g}_A \right)^2,$$

where $\phi^w \geq 0$ is in units of consumption, $\pi_{Ct} \equiv P_t/P_{t-1}$ is the gross CPI inflation rate, and $\iota_w \in [0,1]$ measures the degree to which nominal wage adjustment is indexed to previous price inflation. If $\phi^w = 0$, there is no cost of wage adjustment. Similar to the vacancy cost, the wage adjustment cost is tied to the level of technology $\bar{A}_t$ to ensure balanced growth.

Intermediate input producers sell their output to final producers at a real price φ_t in units of consumption. The present discounted value of the stream of profits is given by:

$$\Pi_{jt}^I \equiv E_t \left\{ \sum_{t=s}^{\infty} \beta_{s,s+1} \left[\varphi_s Y_{js}^I - \frac{w_{js}^n h_{js}}{P_s} L_{js} - \Gamma_{w_js} L_{js} - r_{Ks} K_{js} - \kappa \bar{A}_s \frac{V_{js}^{1+\tau}}{1+\tau} \right] \right\}, \quad (4)$$

where $\beta_{t,t+1} \equiv \beta W_{Ct+1}/W_{Ct}$ is the household stochastic discount factor (the term W_{Ct} denotes the marginal utility of consumption). The representative producer chooses V_{jt}, L_{jt}, and K_{jt} to maximize (4) subject to (2) and (3). When making these decisions, the firm anticipates that both the hourly wage w_{jt} and hours per worker h_{jt} do not depend on the scale of the firm, so that $\partial w_{jt}^n / \partial L_{jt} = \partial h_{jt} / \partial L_{jt} = 0$. As shown below, these results obtain under the standard assumptions of individual Nash wage bargaining and neoclassical determination of hours per worker.

The first-order condition for K_{jt} equates the marginal revenue product of capital to its rental cost:

$$\varphi_t \alpha \left(\frac{K_{jt}}{\bar{A}_t L_{jt} \tilde{h}_{jt}} \right)^{\alpha - 1} = r_{Kt}, \quad (5)$$

implying that the capital-total hours ratio is symmetric across producers, since it only depends on aggregate variables. Let S_{jt}^f denote the Lagrange multiplier on the constraints (3), representing the value to the firm of hiring an extra worker. The first-order condition for L_{jt} implies:

$$S_{jt}^f = (1-\alpha)\, \varphi_t \left(\frac{K_{jt}}{\bar{A} \tilde{h}_{jt} L_{jt}} \right)^{\alpha} \bar{A}_t \tilde{h}_{jt} - \frac{w_{jt}^n h_{jt}}{P_t} - \Gamma_{w_jt} + E_t \beta_{t,t+1} (1-\lambda)\, S_{jt+1}^f. \quad (6)$$

[25]Results are available upon request.

Intuitively, the value of a job to the firm corresponds to the expected, present discounted value of the streams of profits from the match—the difference between the value of the marginal product and the wage payment to the worker minus the cost of adjusting the nominal wage. Finally, the first-order condition for vacancies equates the cost of filling a vacancy to the value of a filled position:

$$\kappa \bar{A}_t \frac{V_{jt}^{\tau}}{q_t} = S_{jt}^{f}. \tag{7}$$

Equations (6) and (7) imply a standard job creation condition:

$$\frac{\kappa \bar{A}_t V_{jt}^{\tau}}{q_t} = (1-\alpha)\varphi_t \left(\frac{K_{jt}}{\bar{A}\tilde{h}_{jt} L_{jt}}\right)^{\alpha} \bar{A}_t \tilde{h}_{jt} - \frac{w_{jt}^{n} h_{jt}}{P_t} - \Gamma_{w_j t} + \kappa (1-\lambda) E_t \beta_{t,t+1} \frac{\bar{A}_{t+1} V_{jt+1}^{\tau}}{q_{t+1}}.$$

Forward looking iteration of the job creation equation implies that, at the optimum, the expected discounted value of the stream of profits generated by a match over its expected lifetime is equal to the cost of filling a vacancy, $\kappa \bar{A}_t V_{jt}^{\tau}/q_t$.

Hours Determination

As is common practice in the literature, we assume that hours per worker maximize the joint surplus of the firm and the worker.[26] This implies that h_{jt} adjusts to the point where the worker's marginal rate of substitution between consumption and leisure is equal to the value of the marginal value product of an extra hour worked:

$$-\frac{W_{h_{jt}}}{W_{Ct}} = (1-\alpha)\varphi_t \left(\frac{k_{jt}}{\bar{A} L_{jt} \tilde{h}_{jt}}\right)^{\alpha} \bar{A}_t \Delta_{\tilde{h}_j t},$$

where $W_{h_{jt}}$ denotes the worker's marginal disutility from supplying an extra hour and

$$\Delta_{\tilde{h}_j t} \equiv \frac{\partial \tilde{h}_{jt}}{\partial h_{jt}} = \frac{\tilde{h}_{jt}}{h_{jt}} - \phi_h h_{jt} (h_{jt} - h_j).$$

Using the first-order condition for capital, the optimal choice of hours per worker implies:

$$-\frac{W_{h_{jt}}}{W_{Ct}} = (1-\alpha)\varphi_t \left(\frac{r_{Kt}}{\varphi_t \alpha}\right)^{\frac{\alpha}{\alpha-1}} \bar{A}_t \Delta_{\tilde{h}_j t}. \tag{8}$$

[26] Alternatively, we could assume that firms have the right to manage hours or consider Nash bargaining over hours per worker. See footnote 36 in section 4 for a discussion of the performance of the model under these alternative assumptions.

Notice that, while up to a first-order approximation $\tilde{h}_{jt} = h_{jt}$, the hours adjustment cost ϕ_h affects aggregate dynamics through the term $\Delta_{\tilde{h}_j t}$. Equation 8 shows that h_{jt} only depends on aggregate conditions, i.e., $h_{jt} = h_t$ is invariant to the scale of the firm. Moreover, h_{jt} does not directly depend on the hourly wage w_{jt}.

Wage Bargaining

The nominal wage is the solution to an individual Nash bargaining problem, and the wage payment divides the match surplus between workers and firms. Due to the presence of nominal rigidities, we assume that bargaining occurs over the nominal wage rather than the real wage, as in Arseneau and Chugh (2008), Gertler et al. (2008), and Thomas (2008). With zero costs of nominal wage adjustment ($\phi^w = 0$), the real wage is identical to the one obtained from bargaining directly over the real wage. This is no longer the case in the presence of wage adjustment costs. As is standard practice in the literature, the wage bargaining is atomistic, implying that the firm and the worker take K_{jt} and L_{jt} as given at the bargaining stage. Moreover, both parties account for the fact that $\partial h_t / \partial w_{jt} = 0$, as shown above.

Let $\bar{\eta}_t \in (0, 1)$ be the weight given to the worker's individual surplus in Nash bargaining. We assume that $\bar{\eta}_t$ follows the process: $\log \bar{\eta}_t = \rho_{\bar{\eta}} \log \bar{\eta}_{t-1} + (1 - \rho_{\bar{\eta}}) \log \bar{\eta} + \varepsilon_{\bar{\eta}t}$, where $\varepsilon_{\bar{\eta}t} \overset{iid}{\sim} N\left(0, \sigma^2_{\bar{\eta}}\right)$. Exogenous fluctuations in the worker's bargaining power are the counterpart of wage-markup shocks typically assumed in the estimation of New Keynesian models that abstract from search and matching frictions.[27] The firm and the worker maximize the Nash product $\left(S^f_{jt}\right)^{1-\bar{\eta}_t} \left(S^w_{jt}\right)^{\bar{\eta}_t}$, where S^f_{jt} is defined as in (6) and S^w_{jt} denotes the worker surplus:

$$S^w_{jt} = \frac{w^n_{jt}}{P_t} h_t - b\bar{A}_t + \frac{W_{L_t}}{W_{Ct}} + E_t \left[\beta_{t,t+1} (1 - \lambda) S^w_{jt+1} \left(1 - \frac{M_{t+1}}{U_{t+1}} \right) \right]. \tag{9}$$

where W_{L_t} is the disutility from working. The worker's surplus corresponds to the expected present discounted value of wage payments over the lifetime of the match minus the expected present discounted value of the flow value of unemployment, including unemployment benefits from the government $b\bar{A}_t$ (financed with lump sum taxes), and the utility gain from leisure in terms of consumption, W_{L_t}/W_{Ct}.

The first-order condition with respect to w^n_{jt} implies the following sharing rule: $\eta_{w_j t} S^f_{jt} =$

[27] Up to a first-order approximation, wage markup shocks are isomorphic to hours supply shocks in the conventional New Keynesian model. Such equivalence breaks down in the presence of labor-market search and matching frictions.

$(1-\eta_{w_jt})S^w_{jt}$, where η_{w_jt} is the *effective* bargaining share of workers:

$$\eta_{w_jt} \equiv \frac{\bar{\eta}_t h_t}{\bar{\eta}_t h_t - (1-\bar{\eta}_t)\left(\partial S^f_{jt}/\partial w^n_{jt}\right)}.$$

(See Appendix B for the expression of $\partial S^f_{jt}/\partial w^n_{jt}$.) As in Gertler and Trigari (2009), the effective bargaining share is time-varying due to the presence of wage adjustment costs. Absent these costs, the bargaining share is exogenous, $\eta_{w_jt} = \bar{\eta}_t$. Importantly, wage rigidity implies that η_{w_jt} is countercyclical, amplifying employment fluctuations in response to aggregate shocks as first noted by Gertler and Trigari (2009).

It is straightforward to verify that w^n_{jt} does not depend on the scale of the firm. To see this, substitute equation (8) into the definition of the worker's and firm's surplus, S^w_{jt} and S^f_{jt}, and use the first-order condition for capital to eliminate the capital-labor ratio in S^f_t. Then, since all the intermediate firms produce with identical technology $\bar{A}_t$, there is a symmetric equilibrium in which $K_{jt} = K_t$, $L_{jt} = L_t$, $h_{jt} = h_t$, $V_{jt} = V_t$, and $w^n_{jt} = w^n_t$. In turn, nominal hourly wage inflation, defined by $\pi_{wt} \equiv w^n_t/w^n_{t-1}$ is linked to CPI inflation by $\pi_{wt} = (w_t/w_{t-1})\,\pi_{Ct}$, where $w_t \equiv w^n_t/P_t$ denotes the real hourly wage. Finally, searching workers in period t are equal to the mass of unemployed workers: $U_t = 1-(1-\lambda)\,L_{t-1}$.

Final Goods Production

A continuum of monopolistically competitive final-sector firms produce differentiated varieties using the intermediate input. The producer ω faces the following demand: $Y^C_{\omega t} = (P_{\omega t}/P_t)^{-\bar{\theta}_t}\,Y^C_t$, where Y^C_t denotes aggregate demand of the final consumption basket, inclusive of sources besides household consumption.

We introduce price-setting frictions by following Rotemberg (1982) and assume that final producers must pay a quadratic price adjustment cost. We also allow for price indexation by assuming that final producers index price changes to past CPI inflation, so that price adjustment costs take the form:

$$\frac{\phi^p}{2}\left(\frac{P_{\omega t}}{P_{\omega t-1}}\pi_C^{\iota_p-1}\pi_{Ct-1}^{-\iota_p}-1\right)^2 P_{\omega t}Y^C_{\omega t},$$

where $\phi^p \geq 0$ determines the size of the adjustment cost (prices are flexible if $\phi^p = 0$) and $\iota_p \in [0,1]$ is the indexation parameter.

Optimal price setting implies that the (real) output price $P_{\omega t}/P_t$ is equal to a markup over the real marginal cost φ_t:

$$\frac{P_{\omega t}}{P_t} = \frac{\bar{\theta}_t}{\left(\bar{\theta}_t - 1\right)\Xi_{\omega t}}\varphi_t,$$

where

$$\Xi_{\omega t} \equiv 1 - \frac{\phi^p}{2}\left(\pi_{\omega t}\pi_{Ct-1}^{-\iota_p}\pi_C^{\iota_p - 1} - 1\right)^2 + \frac{\phi^p}{\bar{\theta}_t - 1}\left\{\begin{array}{c} \pi_C^{\iota_p - 1}\left(\pi_{\omega t}\pi_{Ct-1}^{-\iota_p}\pi_C^{\iota_p - 1} - 1\right)\pi_{\omega t}\pi_{Ct-1}^{-\iota_p} \\ -E_t\left[\beta_{t,t+1}\left(\pi_{\omega t+1}\pi_{Ct}^{-\iota_p}\pi_C^{\iota_p - 1} - 1\right)\pi_{Ct+1}^{-1}\pi_{\omega t+1}^2\pi_{Ct}^{-\iota_p}\frac{Y_{\omega t+1}^C}{Y_{\omega t}^C}\right] \end{array}\right\},$$

where $\pi_{\omega t} \equiv P_{\omega t}/P_{\omega t-1}$. There are two sources of endogenous markup variation in the model. First, the cost of adjusting prices gives firms an incentive to change their markups over time in order to smooth price changes across periods. Second, exogenous shocks to the firms' market power result in time-varying markups even in the absence of price stickiness. In the symmetric equilibrium, $P_{\omega t} = P_t$ and $\Xi_{\omega t} = \Xi$. As a consequence, $\pi_{\omega t} = \pi_t = \pi_{Ct}$.

Household Budget Constraint and Optimal Intertemporal Decisions

The household enters period t with nominal private bond holdings B_t, earning a gross interest rate i_t. The household also accumulates physical capital and rents it to intermediate input producers in a competitive capital market. Investment in the physical capital stock, I_{Kt}, requires the use of the same composite of all available varieties as the basket C_t. We introduce convex adjustment costs in physical investment and variable capital utilization. The utilization rate of capital is set by the household. Thus, effective capital rented to firms, K_t, is the product of physical capital, $\tilde{K}_t$, and the utilization rate, u_{Kt}: $K_t = u_{Kt}\tilde{K}_t$. Increases in the utilization rate are costly because higher utilization rates imply faster capital depreciation. We assume a standard convex depreciation function: $\delta_{Kt} = \delta_0 + \delta_1\left(u_{Kt} - 1\right) + \delta_2\left(u_{Kt} - 1\right)^2$. Physical capital, $\tilde{K}_t$, obeys a standard law of motion:

$$\tilde{K}_{t+1} = \left(1 - \delta_{Kt}\right)\tilde{K}_t + \bar{P}_{Kt}\left[1 - \frac{\nu_K}{2}\left(\frac{I_{Kt}}{I_{Kt-1}} - \bar{g}_A\right)^2\right]I_{Kt}, \tag{10}$$

where $\nu_K > 0$ is a scale parameter, and $\bar{P}_{Kt}$ is an investment specific shock. The latter is a source of exogenous variation in the efficiency with which the final good can be transformed into physical capital, and thus into tomorrow's capital input.[28] The investment shock evolves via the process $\log\bar{P}_{Kt} = \rho_{\bar{P}_K}\log\bar{P}_{Kt-1} + \varepsilon_{\bar{P}_K t}$, where $\varepsilon_{\bar{P}_K t} \overset{iid}{\sim} N\left(0, \sigma_{\bar{P}_K}^2\right)$.

[28] Justiniano et al. (2010) suggests that this variation might stem from technological factors specific to the production of investment goods, but also from disturbances to the process by which these investment goods are turned into productive capital.

The per-period household's budget constraint is:

$$P_tC_t+P_tI_{Kt}+B_{t+1}=i_tB_t+w_t^nh_tL_t+r_{Kt}P_tK_t+b\bar{A}_t\left(1-L_t\right)P_t+P_t\Pi_t^I+P_t\int_0^1\Pi_t^F\left(i\right)di+T_t^g, \quad (11)$$

where T_t^g is a nominal lump-sum tax from the government.

The household maximizes its expected intertemporal utility subject to (10) and (11). The Euler equation for capital accumulation requires: $\zeta_{Kt}=E_t\left\{\beta_{t,t+1}\left[r_{t+1}u_{Kt+1}+\left(1-\delta_{Kt+1}\right)\zeta_{Kt+1}\right]\right\}$, where ζ_{Kt} denotes the shadow value of capital (in units of consumption), defined by the first-order condition for investment I_{Kt}:

$$\zeta_{Kt}^{-1}=\left[1-\frac{\nu_K}{2}\Gamma_{I_Kt}^2-\nu_K\Gamma_{I_Kt}\left(\Gamma_{I_Kt}+1\right)\right]+\nu_K\beta_{t,t+1}E_t\left[\frac{\zeta_{Kt+1}}{\zeta_{Kt}}\left(\Gamma_{I_Kt+1}\right)\left(\Gamma_{I_Kt+1}+1\right)^2\right],$$

where $\Gamma_{I_Kt}\equiv\left(I_{Kt}/I_{Kt-1}\right)-1$. The optimal condition for capital utilization implies: $r_{Kt}=\zeta_{Kt}[\delta_{K1}+\delta_{K2}(u_{Kt}-1)]$. Finally, the Euler equation for bond holdings implies: $1=i_tE_t\left[\beta_{t,t+1}/\left(1+\pi_{Ct+1}\right)\right]$.

The Government and Market Clearing

Fiscal policy is fully Ricardian. The government finances its budget deficit with lump-sum taxes each period. Public spending is determined exogenously, $G_t=\bar{g}_t$, where the exogenous government spending shock $\bar{g}_t$ follows the process $\log\bar{g}_t=\rho_{\bar{g}}\log\bar{g}_t+\left(1-\rho_{\bar{g}}\right)\log\bar{g}+\varepsilon_{\bar{g}t}$, with $\varepsilon_{\bar{g}t}\overset{iid}{\sim}N\left(0,\sigma_{\bar{g}}^2\right)$.

The monetary authority sets the nominal interest rate following a feedback rule of the form

$$\frac{i_t}{i}=\left(\frac{i_{t-1}}{i}\right)^{\varrho_i}\left[\left(\frac{\pi_{Ct}}{\pi_C}\right)^{\varrho_\pi}\left(\frac{Y_{gt}}{Y_g}\right)^{\varrho_Y}\right]^{1-\varrho_i}\left(\frac{Y_{gt}}{Y_{gt-1}}\right)^{\varrho_{dY}}\bar{\imath}_{it}, \quad (12)$$

where i is the steady state of the gross nominal interest rate. The interest rate responds to deviations of inflation and the GDP gap, Y_{gt}, from their long-run targets, as well as to deviations of the growth rate of the GDP gap, Y_{gt}/Y_{gt-1}. GDP is defined as $Y_t\equiv C_t+I_{Kt}+G_t$. Consistent with Woodford (2003), we define the GDP gap as the deviation of model GDP from its level prevailing under flexible prices and wages and absent inefficient shocks (i.e., absent markup and bargaining power shocks). The monetary policy rule is subject to a shock, $\bar{\imath}_{it}$, which evolves according to $\log\bar{\imath}_{it}=\rho_{\bar{\imath}}\log\bar{\imath}_{it-1}+\varepsilon_{\bar{\imath}t}$, with $\varepsilon_{it}\overset{iid}{\sim}N\left(0,\sigma_{\bar{\imath}}^2\right)$.

In the symmetric equilibrium, bonds are zero in net supply: $B_t=B_{t+1}=0$. Thus, combining the household's and government's budget constraints yields the following aggregate resource constraint:

$$Y_t^C\left[1-\frac{\nu}{2}\left(\pi_{Ct}\pi_C^{\iota_p-1}\pi_{Ct-1}^{-\iota_p}-1\right)^2\right]=C_t+I_{Kt}+\kappa_t\bar{A}_tV_t+G_t. \quad (13)$$

Intuitively, total output produced by firms must be equal to the sum of market consumption, investment in physical capital, the costs associated to job creation, the purchase of goods from the government, and the real cost of changing prices. Finally, labor market clearing implies $Y_t^C = Y_t^I$.

The model contains 15 equations that determine 15 endogenous variables: i_t, π_{Ct}, π_{wt}, C_t, L_t, V_t, M_t, h_t, w_t, φ_t, $\tilde{K}_{t+1}$, I_{Kt}, ζ_{Kt}, u_{Kt}, r_{Kt}, and 15 definitions (U_t, S_t^f, S_t^w, h_t, q_t, W_{Ct}, W_{ht}, W_{Lt}, $\tilde{h}_{jt}$, $\Delta_{\tilde{h}t}$, δ_{Kt}, κ_t, η_{wt}, Ξ_t, and Y_{gt}). As detailed below, the terms W_{Ct}, W_{ht}, and W_{Lt} depend on the specification of the household's utility, $u(\cdot)$. Additionally, the model features 8 exogenous disturbances: $\bar{g}_{At}$, $\bar{\beta}_t$, $\bar{h}_t$, $\bar{\theta}_t$, $\bar{\eta}_t$, $\bar{P}_{Kt}$, $\bar{\iota}_t$, and $\bar{g}_t$. Consumption, investment, capital, the real wage, and GDP, (together with Y_t^C, S_t^f, S_t^w, and W_{Ct}) fluctuate around a stochastic balanced growth path, since the level of technology has a unit root. We rewrite the model in terms of detrended variables and compute the log-linear approximation around the non-stochastic steady state. The details of these steps can be found in Appendix C, along with the full set of stationarized equilibrium conditions (and their log-linear approximations). We then solve the resulting linear system of rational expectation equations to obtain the transition equations, which are linked to data with an observation equation to form the state-space model used for estimation.

4 Baseline Model: Separable Preferences and Frictionless Hours Adjustment

We first estimate a model that corresponds to the baseline version considered in the literature: separable preferences and frictionless hours-per-worker adjustment—see for instance, Andolfatto (1996), Arseneau and Chugh (2008), Christiano et al. (2011), Merz (1995), Ravenna and Walsh (2012), and Trigari (2009). We set $\phi_h = 0$ and assume that

$$W_t \equiv E_t \sum_{s=t}^{\infty} \beta^{s-t} \bar{\beta}_s \left[\log(C_t - h_C C_{t-1}) - \bar{h}_t \int_0^{L_t} \frac{h_{js}^{1+\omega}}{1+\omega} dj \right],$$

where h_C is the degree of habit formation. Consumption utility is logarithmic to ensure the existence of a balanced growth path in the presence of non-stationary technological progress. This preference specification implies that disutility of labor supply is $W_{Lt} = -\bar{\beta}_t \bar{h}_t h_{jt}^{1+\omega} / (1+\omega)$, while the marginal disutility of working an extra hour is $W_{h_{jt}} = -\bar{\beta}_t \bar{h}_t h_{jt}^{\omega}$. Table A.3 summarizes the equilibrium conditions of the baseline model.

We estimate the model with U.S. quarterly data from 1965:1 to 2007:4. Details of the data construction and linkages to observables are presented in Appendix A. For the baseline estimation, we end the estimation prior to the recent zero lower bound episode.[29] Our initial estimation includes seven observables commonly employed in the literature: the log difference of aggregate consumption, investment, GDP, and real wages, the log difference of the GDP deflator, the Federal Funds rate, and the log of economy-wide total hours worked. [30] To avoid stochastic singularity, we include seven structural shocks. To facilitate comparison with the literature (i.e., Christiano et al., 2011, and Gertler et al., 2008), our baseline specification assumes that shocks to the exogenous component of the worker's bargaining power, $\bar{\eta}_t$, are the only disturbance directly affecting the labor market, i.e., $\bar{h}_t = 1$ for any t.[31]

In addition, we estimate the model including the hours supply shock, $\bar{h}_t$, and one ancillary observable, the log of economy-wide employment.[32] Using information on both margins of labor adjustment helps identify key labor parameters such as the Frisch elasticity. Moreover, the inclusion of the hours supply shock gives the model a better chance to match the dynamics of the labor margins.

We use Bayesian inference methods to construct the parameters' posterior distribution, which is a combination of a prior density for the parameters and the likelihood function, evaluated using the Kalman filter. We take 1.5 million draws from the posterior distribution using the random walk Metropolis-Hastings algorithm. For inference, we discard the first $500,000$ draws and keep one every 50 draws to remove some correlation of the draws.[33]

Prior Distributions

We impose dogmatic priors for some parameters. The household discount factor β is set to 0.99, α is 0.3, and depreciation δ is 0.025. The steady-state price markup is set at 1.1. Steady-state government spending is fixed at 20 percent of GDP, which equals the post-war average for all levels of government spending. Following standard practice in the literature, we use independent evidence for the average quarterly separation rate λ and the elasticity of matches to unemployment, ε. In particular, we choose $\lambda = 0.105$ based on the observation that jobs last on average about two

[29] See Hirose and Inoue (2015) for a discussion of how the ZLB can bias estimates of log-linearized model parameters.

[30] Examples include Christiano et al. (2005), Smets and Wouters (2007), Del Negro et al. (2007), Gertler et al. (2008), and Justiniano et al. (2010).

[31] In section 7, we discuss the alternative possibility of focusing on stochastic fluctuations in the disutility of hours worked, $\bar{h}_t$, while keeping constant the worker's bargaining power, i.e., $\bar{\eta}_t = 1$.

[32] This is observationally equivalent to estimating the model using hours per worker and employment as observables, since we abstract from measurement error.

[33] We set the step size to ensure the acceptance rate is in the range of 20 to 40 percent for all variations of the estimated model. Convergence diagnostics include cumulative sum of draws (cumsum) statistics and Geweke's Separated Partial Means (GSPM) test. Results are available from the authors.

and half years in the U.S. economy (Shimer, 2005). We set ε to be equal to 0.5, the midpoint of the evidence typically cited in the literature and within the range of plausible values (0.5 to 0.7) reported by Petrongolo and Pissarides (2006). Finally, we set the cost of posting a vacancy, κ, and the matching efficiency parameter, χ, to match the quarterly average job finding probability, M/U, and the average probability of filling a vacancy, q. For the U.S., the former is equal to 0.95, while the latter is 0.9 (Shimer, 2005).

Table 2 lists the prior distributions for the remaining parameters in the columns labeled "Priors." Our priors for common parameters are similar to those in Smets and Wouters (2007). We set the price stickiness parameter, ϕ^p, to a value that would replicate the frequency of price adjustment in a Calvo-type Phillips curve in the absence of strategic price complementarities. For comparability with the literature, we directly estimate the related Calvo parameter ξ^p.[34] In contrast, no direct mapping to a Calvo-type wage Phillips curve exists, even in a linearized setup. Thus, we employ a prior for ϕ^w that permits a broad degree of stickiness. The estimated labor market parameters include the steady-state value of the workers' bargaining power $\bar{\eta}$, the replacement rate b/wh, and the degree of convexity in the cost of posting vacancies τ. The first two have priors similar to those in Gertler et al. (2008). Finally, the bargaining power, price markup, and investment shocks are normalized to enter with a unitary coefficient in the log-linearized equations that determine wages, inflation, and investment, respectively. The priors for the standard deviations of shocks are chosen to generate similar volatilities between the variables they directly impact and their data counterparts, as is common practice in the literature.

Posterior Estimates

Table 2 reports the posterior estimates of the baseline model presented in section 3. As previously discussed, we estimate two versions of this model. The first includes seven observables and seven shocks: TFP, investment, preference, government spending, interest rate, price markup, and bargaining shocks. Parameter estimates from this version are listed under the column "7 obs." The second version includes an additional observable, employment, and an additional labor market shock, the hours-supply shock $\bar{h}_t$. Parameter estimates from this version are listed in the column "Baseline" under the headings "8 obs" in Table 2. For a discussion of the posterior estimates relative to the literature, see Appendix D.

[34] ξ^p is related to ϕ^p via the mapping $\phi^p = \left[\left(\bar{\theta}-1\right)/\bar{\theta}\right]\xi^p/(1-\xi^p)(1-\xi^p\beta)$.

Table 2: Posterior Distributions for Estimated Parameters.

Parameter	**Prior**			**Posterior**					
				7 obs		**8 obs**			
				Baseline Model		**Baseline Model**		**Preferred Model**	
	Dist.*	Mean	Std.	Mean	90% Int	Mean	90% Int	Mean	90% Int
Preferences									
h_C, habit formation	B	0.5	0.1	0.79	[0.73, 0.83]	0.68	[0.63, 0.72]	0.79	[0.73, 0.84]
ω, inverse Frisch	G	2	0.5	3.34	[2.49, 4.33]	6.98	[5.83, 8.24]	2.74	[1.94, 3.68]
Frictions and Production									
$100 \log \bar{g_A}$, growth rate	N	0.4	0.03	0.41	[0.37, 0.45]	0.40	[0.36, 0.44]	0.41	[0.36, 0.45]
ν_K, investment adj. cost	N	4	1.5	4.89	[3.15, 6.93]	6.97	[5.48, 8.54]	7.76	[6.10, 9.50]
ϕ_h, hours adj. cost	N	4	1.5	n.e.		n.e.		6.17	[4.53, 7.91]
ς, capital utilization	B	0.5	0.1	0.54	[0.45, 0.62]	0.51	[0.43, 0.58]	0.44	[0.36, 0.52]
$\bar{\eta}$, workers bargaining power	B	0.5	0.1	0.76	[0.63, 0.86]	0.56	[0.44, 0.68]	0.50	[0.38, 0.62]
$b/(w * h)$, replacement rate	B	0.5	0.1	0.59	[0.48, 0.69]	0.56	[0.41, 0.69]	0.47	[0.34, 0.58]
τ, convexity vacancy cost	G	2	0.5	1.27	[0.80, 1.83]	2.67	[2.05, 3.38]	2.74	[2.10, 3.48]
$\phi^w/1000$, wage stickiness	N	2	0.4	2.86	[2.31, 3.42]	2.53	[2.00, 3.07]	2.59	[2.07, 3.13]
ι_w, wage partial indexation	B	0.5	0.15	0.77	[0.61, 0.90]	0.69	[0.54, 0.84]	0.71	[0.56, 0.85]
ξ^p, price stickiness	B	0.66	0.1	0.86	[0.83, 0.89]	0.90	[0.87, 0.93]	0.90	[0.87, 0.93]
ι_p, price partial indexation	B	0.5	0.15	0.13	[0.06, 0.21]	0.12	[0.05, 0.21]	0.12	[0.05, 0.21]
Monetary policy									
ϱ_π, interest resp. to inflation	N	1.7	0.3	1.78	[1.55, 2.05]	1.21	[1.01, 1.43]	1.32	[1.12, 1.53]
ϱ_Y, interest resp. to Y gap	G	0.125	0.1	0.05	[0.02, 0.09]	0.10	[0.06, 0.14]	0.07	[0.03, 0.12]
ϱ_{dY}, interest to Y gap growth	N	0.13	0.05	0.34	[0.28, 0.40]	0.31	[0.25, 0.36]	0.28	[0.23, 0.34]
ϱ_i, resp. to lagged interest rate	B	0.75	0.1	0.76	[0.72, 0.80]	0.73	[0.68, 0.77]	0.75	[0.70, 0.79]
Shocks									
ρ_{g_A}, technology	B	0.5	0.2	0.14	[0.05, 0.24]	0.07	[0.02, 0.13]	0.10	[0.03, 0.19]
ρ_β, preference	B	0.5	0.2	0.70	[0.59, 0.79]	0.84	[0.78, 0.89]	0.67	[0.52, 0.79]
ρ_{P_K}, investment	B	0.5	0.2	0.84	[0.78, 0.90]	0.20	[0.10, 0.30]	0.20	[0.11, 0.30]
ρ_θ, price markup	B	0.5	0.2	0.88	[0.81, 0.93]	0.82	[0.74, 0.88]	0.85	[0.77, 0.91]
ρ_η, bargaining	B	0.5	0.2	0.37	[0.24, 0.51]	0.16	[0.06, 0.26]	0.16	[0.07, 0.27]
ρ_g, govt cons	B	0.5	0.2	0.99	[0.98, 0.99]	0.99	[0.98, 0.99]	0.98	[0.98, 0.99]
$\rho_{\bar{\imath}}$, monetary shock	B	0.5	0.2	0.13	[0.05, 0.22]	0.15	[0.06, 0.25]	0.16	[0.07, 0.26]
ρ_h, hours shock	B	0.5	0.2	n.e.		0.97	[0.94, 0.98]	0.97	[0.96, 0.99]
$100\sigma_{g_A}$, technology	IG	0.5	1	0.83	[0.75, 0.92]	1.01	[0.92, 1.11]	1.07	[0.97, 1.19]
$100\sigma_\beta$, preference	IG	1	1	2.43	[2.00, 2.95]	2.06	[1.78, 2.39]	2.87	[2.30, 3.63]
$100\sigma_{P_K}$, investment	IG	0.1	1	0.71	[0.60, 0.83]	1.36	[1.18, 1.56]	1.37	[1.19, 1.57]
$100\sigma_\theta$, price markup	IG	0.1	1	0.06	[0.05, 0.07]	0.06	[0.05, 0.08]	0.06	[0.05, 0.07]
$100\sigma_\eta$, bargaining	IG	1	1	4.11	[3.36, 4.88]	4.90	[4.28, 5.56]	4.88	[4.27, 5.52]
$100\sigma_g$, govt cons	IG	0.5	1	1.47	[1.34, 1.61]	1.53	[1.39, 1.67]	1.57	[1.43, 1.72]
$100\sigma_{\bar{\imath}}$, monetary shock	IG	0.1	1	0.24	[0.21, 0.26]	0.24	[0.22, 0.27]	0.24	[0.21, 0.26]
$100\sigma_{\bar{h}}$, hours supply shock	IG	0.5	1	n.e.		3.49	[2.97, 4.05]	3.51	[2.93, 4.17]
Implied from Estimated Model									
β_h					[0.03, 0.22]		[0.16, 0.76]		[0.13, 0.56]
β_L					[0.64, 1.21]		[0.22, 0.89]		[0.20, 0.71]
β_{cov}					[-0.35, 0.25]		[-0.43. 0.37]		[-0.05, 0.44]
Log marginal data density							-1073		-1024
2 ln(Bayes Factor) vs. Preferred							98		0

*Distributions: N: Normal; G: Gamma; B: Beta; IG: Inverse Gamma.

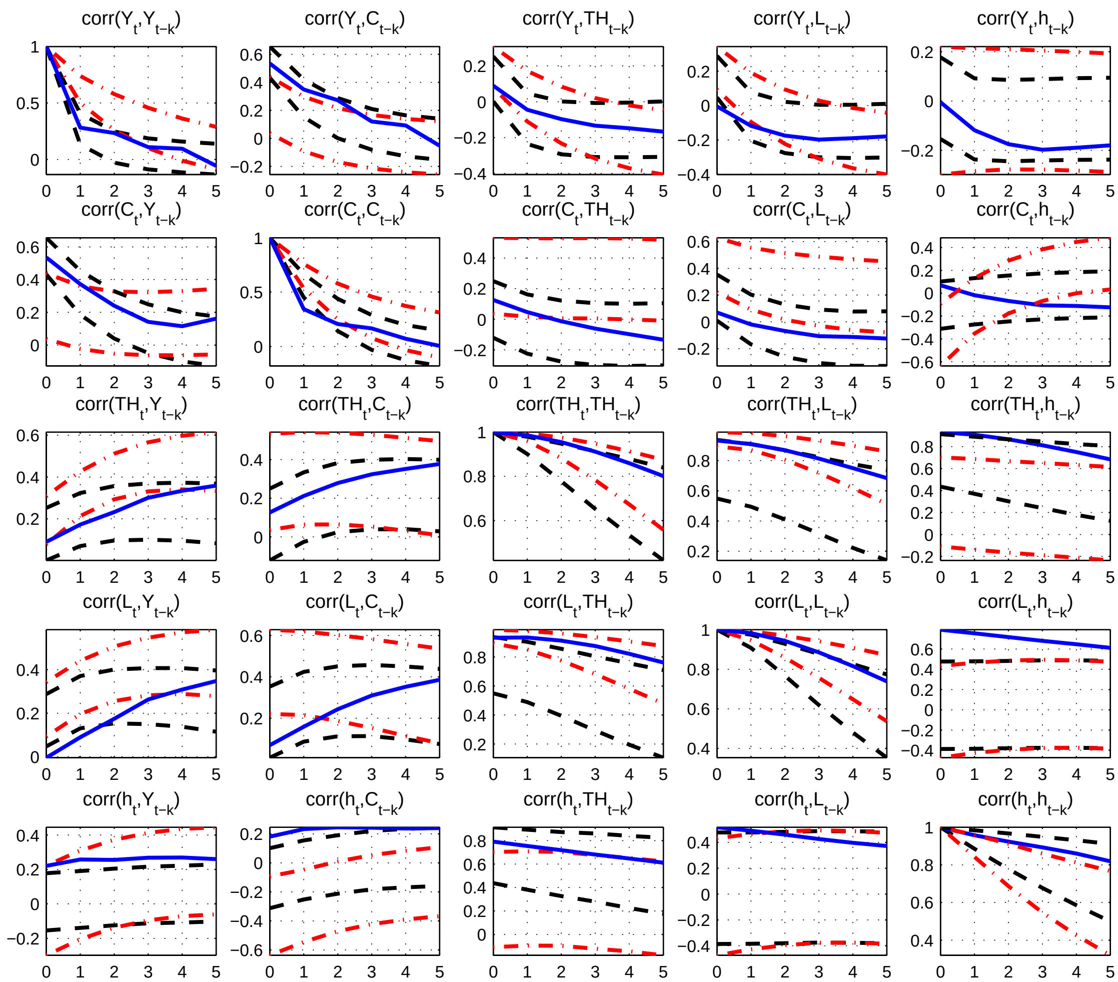

Figure 2. Correlograms from the data (solid lines) and 90 percent posterior intervals from 1) the baseline model with seven observables (dotted dashed lines) and 2) the baseline model with eight observables (dashed lines).

Model Fit

To understand how well the baseline model fits the data, we compare a set of statistics implied by the model to their data counterparts. Figure 2 plots the correlogram for several aggregate macroeconomic and labor market variables in the data (solid lines), as well as the 90-percent posterior intervals implied by both parameter and small sample uncertainty from the seven observable case (dotted lines) and the eight observable case (dashed lines).[35] We discuss the results of each case in turn.

The literature shows that the baseline model with only the extensive margin and seven observables—

[35] We sample 10,000 draws from the posterior. For each parameter draw, we generate 100 samples of the observable variables from the model with the same length as our dataset, after first discarding 100 initial observations. We compute statistics for each of these samples.

including either total hours or employment—is able to reproduce the joint dynamics of employment and macroeconomic variables (see, for instance, Gertler et al., 2008). Estimates of a version of our baseline model with only the extensive margin are in line with these results (results available upon request). However, when the intensive margin is introduced in the model, its ability to account for the correlations between labor market variables and aggregate macroeconomic series is significantly impaired, as evidenced by comparing the data (solid lines) and model (dotted lines) statistics in figure 2. First, the baseline model estimated with seven observables does not capture the positive correlation between hours and employment nor the relative contributions of the labor margins to the variance of total hours. In particular, the model assigns an almost exclusive role to employment, as the 90 percent posterior bands for the share of the labor margin to the variance of total hours (β_L) are between 0.64 and 1.21 (see Table 2), while the data counterpart is only 0.51. The β_{cov} ranges from -0.35 to 0.25, well short of the positive comovement (0.31) between hours and employment observed in the data. Moreover, the model overstates the correlation between the growth rate of output with total hours or employment at various leads and lags. Even though it correctly reproduces the correlogram between total hours and consumption growth, it does so with a counterfactual comovement of the individual margins with respect to consumption.

Prima facie, the poor performance of the model with seven observables could reflect that the model is estimated with only one labor market observable. However, simply adding information about the labor market by increasing the set of observables to include simultaneously employment (or hours per worker) and total hours does not improve the performance of the model. The dashed lines of figure 2 report the 90 percent posterior correlogram bands for the baseline model when employment data and an hours supply shock are incorporated in the estimation. The correlation of hours per worker and consumption growth is still too low relative to the data, while the correlation between employment and output growth is instead too high. Despite providing more information about labor market dynamics, the model still fails to ensure the positive correlation between hours and employment, and the β_{cov} ranges from -0.43 to 0.37 (see Table 2). In addition, this version of the model tends to overstate the importance of hours per worker relative to the data, as the posterior for β_h ranges from 0.16 to 0.76, whereas its value is 0.18 in the data. All in all, the baseline model—independently of the shocks considered or the observables included in the estimation—is unable to replicate satisfactorily the correlation structure between the aggregate macroeconomic series and the labor market variables.

The main issue is that hours per worker tends to be too countercyclical in the model.[36] As detailed in Appendix E, such counterfactual correlations reflect the negative comovement between the labor margins following standard supply and demand shocks, as well as in response to labor market shocks (either wage-bargaining shocks or hours-supply shocks). In particular, hours per worker fall in response to both positive technology and demand shocks, since wealth effects reduce labor supply. By contrast, employment rises, since the surplus of hiring a worker increases in the presence of nominal and real wage rigidities. Moreover, the response of hours per worker is as large as employment for several of the shocks we consider.

As a final check on the performance of the baseline model, we perform the following counterfactual. We use the posterior mean estimates from the baseline model with seven observables to obtain model time-series using the two-sided Kalman filter. Figure 3 displays the model-implied labor market variables (dashed lines), as well as the data (dotted-dashed lines). Since total hours are included as an observable, by construction the two-sided Kalman filter ensures the baseline model perfectly matches this series. However, the model matches total hours only with counterfactual employment and hours per worker series, suggesting short-comings in the internal propagation of the model.

To address the shortcomings of the baseline model, in the next section we propose two modifications that reconcile the model with the data. First, we introduce preferences with a flexible parametrization of the strength of the short-run wealth effect on hours supply. In addition, to discipline the movement in hours worked, we allow for non-zero adjustment costs to the intensive margin, ϕ_h. These two ingredients provide a parsimonious strategy to reproduce the correlation of the labor market variables and the macroeconomic series.

5 Alternative Model: Parametrized Wealth Effects and Costly Hours Adjustment

This section contains the econometric analysis of the model with alternative preferences and hours adjustment costs, which we reference as our preferred model. We first introduce the alternative

[36] Notice that under the alternative assumption that firms have the right to manage (RTM) hours, hours supply considerations (and thus wealth effects) do not affect h_t. Nevertheless, an estimated version with RTM verifies that the lack of positive comovement between L_t and h_t persists—under RTM, h_t equates the marginal product of an hour worked to w_t, implying that, with wage rigidities and pre-determined capital, h_t falls when L_t increases, other things equal. In contrast, the comovement between h_t and L_t improves with Nash bargaining over hours per worker, as long as the worker's bargaining share is not constrained to be symmetric to the corresponding share in wage Nash bargaining. This result reflects the additional degree of freedom stemming from the extra bargaining parameter. Results are available upon request.

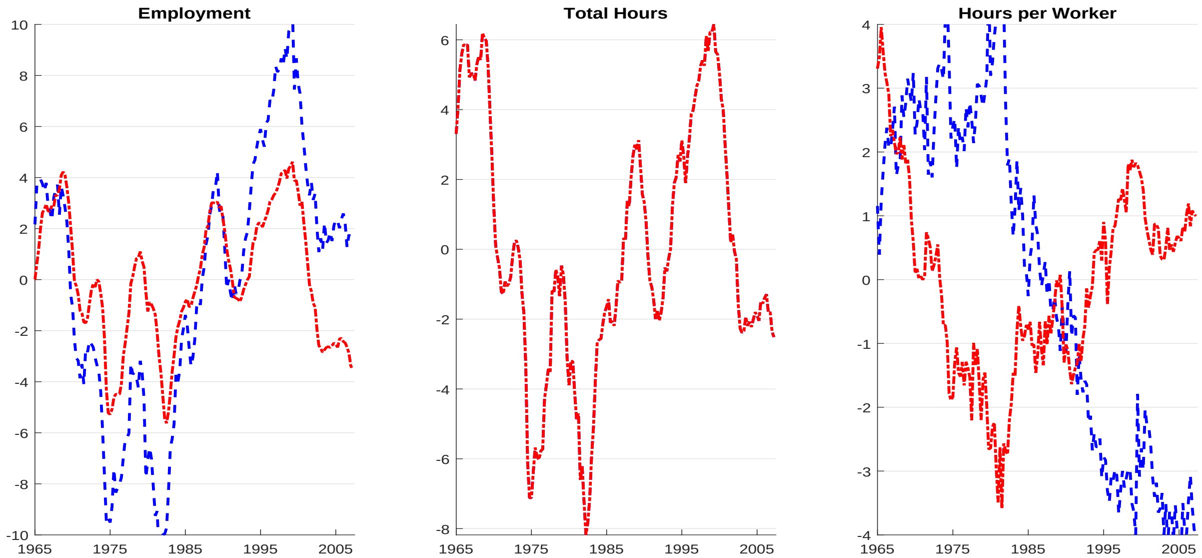

Figure 3. Fitted and counterfactual variables. Blue dashed lines are simulated from the posterior mean estimates of the baseline model with seven structural shocks. Red dotted-dashed lines denote the data.

functional form for the household's utility. Next, we discuss priors on new parameters and assess the fit of the model relative to the data.

Parametrized Wealth Effects in Labor Supply

We modify the period utility function to encompass an alternative preference specification that features a flexible parameterization of the strength of the short-run wealth effect on the labor supply. We consider the class of preferences first introduced by Jaimovich and Rebelo (2009) (JR henceforth). Following Schmitt-Grohe and Uribe (2007), we modify the original JR specification to allow for internal consumption habit formation. The period utility function of the representative household now is given by:

$$W_t \equiv E_t \sum_{s=t}^{\infty} \beta^{s-t} \bar{\beta}_s \left[\log \left(C_t - h_C C_{t-1} - \bar{h}_t X_t \int_0^{L_t} \frac{h_{jt}^{1+\omega}}{1+\omega} dj \right) \right], \tag{14}$$

where $\gamma \in (0,1]$ and $X_t = (C_t - h_C C_{t-1})^{\gamma} X_{t-1}^{1-\gamma}$. The parameter γ governs the magnitude of the wealth elasticity of labor supply. As $\gamma \to 0$, in the absence of habit formation, and abstracting from time variation in the number of employed family members, this is the preference specification considered by Greenwood et al. (1988). This special case induces a supply of labor that is independent of the marginal utility of consumption. As a result, when γ is small, anticipated changes in income will not affect the current labor supply. As γ increases, the wealth elasticity of labor supply rises. In the polar case in which γ is unity, per-period utility becomes a product of habit-adjusted consumption and a function of hours worked.[37]

Notice that the marginal disutility from labor supply, $W_{h_{jt}}$, now is defined as:

$$W_{h_{jt}} \equiv -\Psi_t^{-1}\bar{\beta}_t\bar{h}_t h_{jt}^{\omega} X_t,$$

where $\Psi_t \equiv C_t - h_C C_{t-1} - \bar{h}_t X_t \int_0^{L_t} \left[h_{jt}^{1+\omega} / (1+\omega) \right] dj$. Thus, the marginal rate of substitution between hours and consumption for worker j, $-W_{h_{jt}}/W_{Ct}$, continues to depend on aggregate variables, with the exception of hours worked, h_{jt}. As a result, equation (8) implies that hours per worker, h_{jt}, continue to depend only on aggregate conditions, so that $h_{jt} = h_t$ (and thus $\tilde{h}_{jt} = \tilde{h}_t$). Moreover, relative to the baseline model, the equilibrium wage differs only because of the different definitions of the value of the marginal product of labor and the flow value of unemployment implied by the parametrized wealth effect on the labor supply. In particular, we now have $W_{L_t} = -\Psi_t^{-1}\bar{\beta}_t\bar{h}_t h_t^{1+\omega} X_t$.

Overall, our modifications affect three equilibrium conditions—equations (4), (14), and (15) in Table A.3—and three definitions—equations D.4-D.6 in Table A.3 in Appendix C.

Estimation and Model Performance

We estimate the model with the same eight observables discussed above. For symmetry, we employ the same prior for hours adjustment costs as for investment adjustment costs, a normal distribution centered at 4 with a standard deviation of 1.5. This prior is diffuse enough to allow positive mass over a wide range of low and high adjustment cost values. We use a dogmatic prior for the parameter governing the strength of the wealth effect in labor supply, setting $\gamma = 0.01$. This value is sufficiently small to approach the limiting case of no wealth effects. In addition, we also estimate a version of the model with a Beta prior for γ centered at 0.5 with a standard deviation of 0.1. The posterior mean for γ in this case is 0.16, outside the 90 percent prior bands. Lowering the prior mean of γ results in lower posterior estimates and similar transmission mechanisms as our calibrated version. The priors for the remaining parameters are the same as those discussed in Section 4.

[37]The presence of employed and unemployed workers implies that even with full risk-sharing within the household, the specification in equation (14) cannot be obtained by aggregating primitive utility functions for employed and unemployed workers. We have considered an alternative version of the model that features JR preferences for employed workers and a distinct utility function for unemployed family members. We then aggregate across agents, maintaining the assumption of full risk sharing within the household. Details are available upon request.

Table 2 reports the log marginal data densities and Bayes factors for the baseline and preferred models. Bayes factors quantify the relative support of two competing specifications given the observed data and are calculated from marginal data densities. Log marginal data densities are computed using Geweke's (1999) modified harmonic mean estimator with a truncation parameter of 0.5.[38] Kass and Raftery (1995) suggest that if twice the natural logarithm of the Bayes factor is greater than 2, then there is positive evidence in favor of the first model. Values greater than 10 suggest very strong evidence. The baseline model has a value substantially larger than 10, suggesting the data have strong preference for the model with JR preferences and hours adjustment costs. Furthermore, as shown in section 7, including only JR preferences or hours adjustment costs improves the model fit relative to the baseline model, while the inclusion of both is strongly preferred by the data.

Figure 4 plots the correlogram for several aggregate macroeconomic and labor market variables in the data (solid lines), as well as the 90 percent posterior intervals implied by both parameter and small sample uncertainty from this preferred model (dotted lines) and the baseline model with eight observables (dashed lines). In almost all cases, the correlogram bands for the preferred model encapsulate the data counterparts, whereas the baseline model often fails to account for the cross-correlation structure of labor variables and macroaggregates. The preferred specification also implies variance decompositions of total hours more united with the data counterparts (see Table 2): β_h ranges from 0.12 to 0.54, β_L from 0.20 to 0.72, and β_{cov} from -0.05 to 0.44.

The inclusion of JR preferences significantly improves the performance of the model. As described in the previous section, JR preferences reduce the strength of the short-run wealth effect on the labor supply. This mitigates the effect of variations in consumption on the marginal rate of substitution and makes hours per worker more responsive to changes in the value of the marginal product of hours. In turn, the increased comovement between hours per worker and employment strengthens the comovement of hours per worker with both output and investment. This also explains the data's preference for large adjustment costs to hours, as they readjust the variability of hours to be comparable to the data. Without adjustment costs to hours, hours per worker tend to be too volatile, implying that hours per worker and employment contribute roughly equally to

[38] Bayes factors convey the same kind of information as the Bayesian Information Criterion, see Kass and Raftery (1995). Model rankings are invariant to alternative truncation parameter choices. We restrict analysis to the parameter subspace that delivers a unique rational expectations equilibrium and denote this subspace as Θ_D. In addition, we restrict parameters to ensure the steady-state wage lies within the feasible bargaining set. Let $I\{\theta \in \Theta_D\}$ be an indicator function that is one if the parameter vector θ is in the determinacy region and zero otherwise. Then, the joint prior distribution is defined as $p(\theta) = (1/c)\,\tilde{p}(\theta)I\{\theta \in \Theta_D\}$, where $c = \int_{\theta\in\Theta_D} \tilde{p}(\theta)d\theta$ and $\tilde{p}(\theta)$ denotes the joint prior density. Higher log marginal data density values imply greater fit.

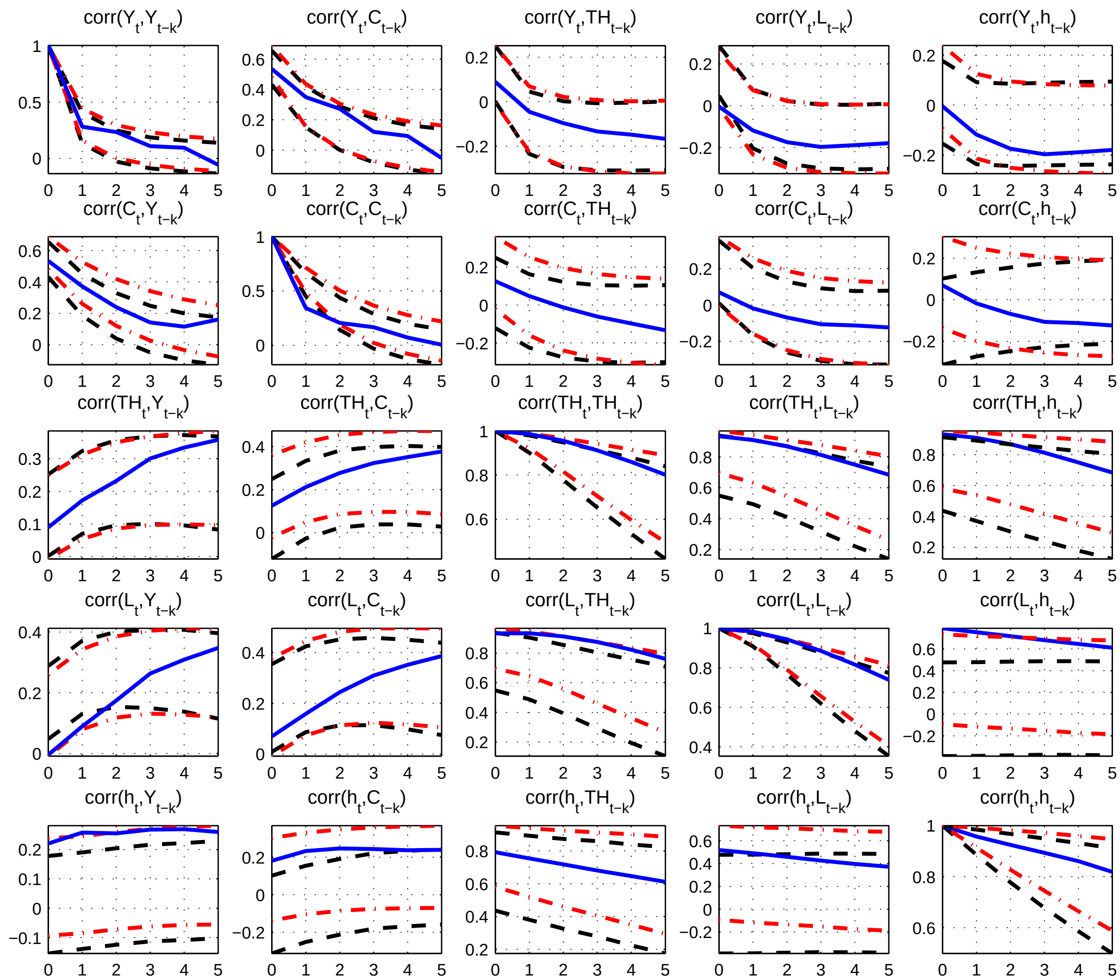

Figure 4. Correlograms from the data (blue solid lines) and 90 percent posterior intervals from 1) the preferred model with JR preferences and hours adjustment costs (red dotted dashed lines) and 2) the baseline model with eight observables (black dashed lines).

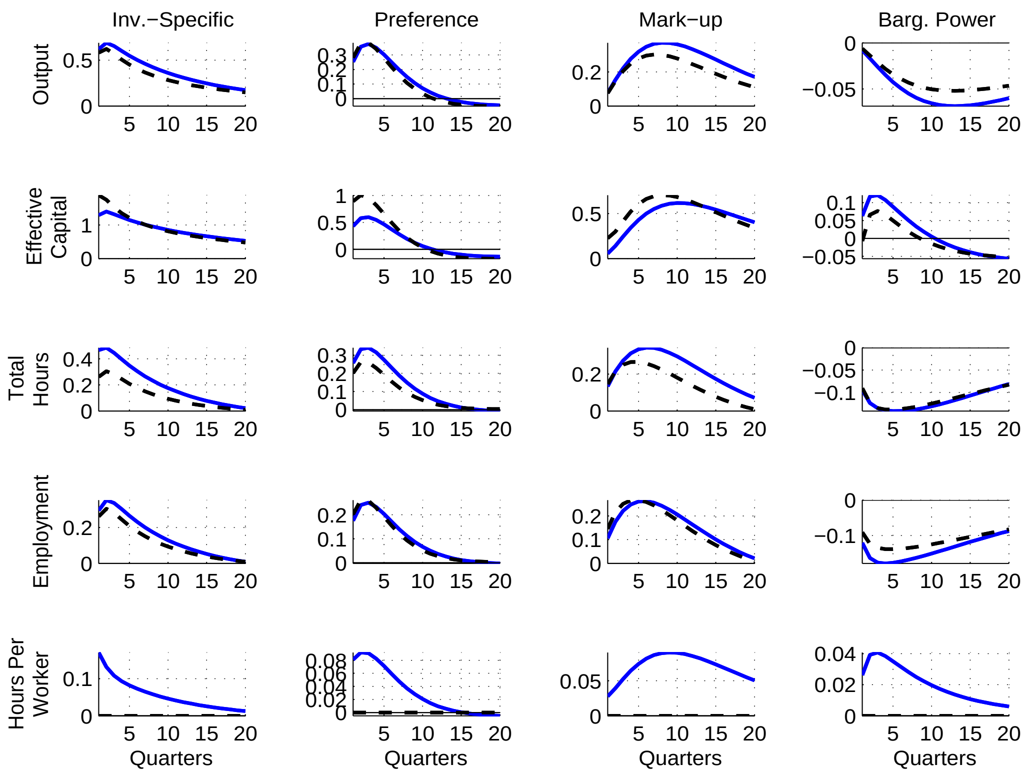

Figure 5. Impulse response following a one standard deviation innovation at the posterior mean. Solid lines denote the responses of the preferred model, while dashed lines correspond to the counterfactual economy without adjustment in hours per worker.

total hours variation (see Table 3). Note that as reported in Table 2, the estimated persistence and standard deviations of innovations are similar across the baseline and preferred specifications, suggesting that the improved fit can be traced to an improvement in the propagation mechanism rather than to different estimates of the shock processes.

To substantiate this intuition, we study the propagation mechanism of individual shocks. We consider the dynamics following innovations to investment-specific productivity, preference, firms' mark-up, and worker's bargaining power. In the preferred model, these shocks account for the majority of the variance of total hours and employment.[39] Figure 5 (solid lines) reports the impulse responses from posterior mean estimates for output, effective capital, employment, and hours per worker. In all cases, responses are computed following a one standard deviation shock.

As illustrated by figure 5, standard supply and demand shocks—investment-specific shocks, preference shocks, and price-markup shocks—induce positive comovement between the labor margins.[40] This positive comovement is key for matching the unconditional positive correlation between

[39] Appendix F presents the variance decompositions for a range of variables.

[40] Neutral technology, monetary policy, and government spending, not pictured in figure 5, also result in positive

the labor margins. The main difference in propagation relative to the baseline model is that the low wealth effect on the labor supply implies that hours per worker increase in response to positive supply and demand shocks, since hours per worker comove more tightly with the value of the marginal product of hours.[41] By contrast, labor-market shocks–shocks to workers' bargaining power and hours supply shocks—induce negative comovement. For instance, as displayed by the last column of figure 5, an exogenous increase in workers' bargaining power reduces employment—since workers appropriate a larger share of the surplus through higher wages—and it increases hours per worker, the relatively cheaper labor margin. The shock is recessionary as it increases the cost of production, leading output, investment and consumption to decline.

The Role of Hours Supply Shocks

While parametrized wealth effects and hours adjustment costs are key ingredients for the model to reproduce the empirical covariances of labor market variables, hours supply shocks remain an important contributor for the variance of hours per worker— $\bar{h}_t$ accounts for about 60 percent of the volatility of h_t. A natural question concerns the interpretation of hours supply shocks in the context of the model. One possibility is that $\bar{h}_t$ simply reflects measurement error. To rule this hypothesis, we estimate an alternative version of the model that additionally allows for measurement error in each observable. Even in this case, hours supply shocks still remain an important contributor to fluctuations in hours per worker (results available upon request).

A closer look at the model equilibrium conditions presents a simple structural interpretation for the role of $\bar{h}_t$ at business cycle frequencies. Consider the log-linear approximation of the intratemporal condition for optimality in hours with the assumption that steady-state hours per worker are normalized to one:

$$\hat{\bar{\beta}}_t - \frac{1}{\Psi}\left[\hat{C}_t C - h_C \frac{C}{g_A}\left(\hat{C}_{t-1} - \hat{g}_{At}\right) - \frac{LX}{1+\omega}\left(\hat{L}_t + (1+\omega)\,\hat{h}_t + \hat{X}_t\right)\right] + \hat{h}_t + \hat{X}_t - \hat{u}_{Ct}$$
$$= \hat{\varphi}_t + \alpha\left(\hat{u}_{Kt} + \hat{\bar{K}}_t - \hat{g}_{At} - \hat{L}_t - \hat{h}_t\right) - \phi_h \hat{h}_t - \left(\omega + \frac{XL}{(1+\omega)\Psi}\right)\hat{\bar{h}}_t,$$

where hats denote log-deviations. The right-hand side of this equation shows that $\bar{h}_t$ acts as a time-varying shifter of the marginal product of one hour worked, consistent with the empirical observation that changes or differences in working hours do not entail the same changes or differences in effective

comovement in hours per worker and employment.

[41] See Appendix E for a detailed comparison of impulse responses in the baseline and preferred model.

labor input (Pencavel, 2015). Thus, $\bar{h}_t$ captures cyclical fluctuations in unobservable utilization of hours per worker, reflecting variations in unobserved worker effort (see, for instance, Kimball et al., 2006).[42] In addition, $\bar{h}_t$ captures exogenous fluctuations in the value of nonworking time, i.e., the value of the opportunity cost of employment.[43]

6 Hours and Employment in Post-War U.S. Business Cycles

We now use the preferred model to empirically study the cyclical behavior of hours and employment in U.S. data. We focus on U.S. business cycle recoveries—i.e., the progression of the economy after having hit the trough of a recession—as there has been renewed interest in the topic in policy circles (see Bernanke, 2003).

The impulse-response analysis discussed above rationalizes the observed time-varying comovement between the margins of labor adjustment documented in section 2. When recoveries feature a prominent role for standard supply and demand shocks, hours per worker and employment comove positively. By contrast, when labor market shocks have a larger role, the adjustment along the two margins displays a much lower correlation. The historical decompositions of employment and hours per worker from the preferred model (presented in Appendix G) show that structural innovations responsible for employment and hours per worker fluctuations in recoveries are consistent with these comovements. For example, recessions and recoveries of 1970, 1975, and 1982 are predominantly driven by investment-specific shocks, while those in 1991 and 2001 feature a more significant role for labor-market shocks.[44]

Our model provides an ideal laboratory to quantify the contribution of the intensive margin for employment outcomes. Towards this goal, we perform the following counterfactual. First, we use the posterior mean estimates of the preferred model and the two-sided Kalman filter to construct smoothed estimates of the structural shocks and model variables. We then construct a counterfactual time series where hours are held constant at their steady-state value and compare

[42] Marchetti and Nucci (2014) document a hump-shaped profile of labor effort at business cycle frequencies. Notice that $\bar{h}_t$ may also capture in reduced-form other unmodeled features of hours adjustment such as overtime hours. A formal assesment of the quantitative importance of this alternative interpretation is precluded by the absence of economy-wide data for overtime hours in the U.S. economy.

[43] The estimated preferred model is not only consistent with the labor margins emphasized in this paper, but also with the properties of the opportunity cost of employment emphasized in Chodorow-Reich and Karabarbounis (2016). To demonstrate this, we use the observables and the two-sided Kalman filter at the posterior mean estimates to generate smoothed, historical estimates of model variables, which by construction perfectly match employment and the other macro observables to the data. The model-implies series generate 1) the opportunity cost of employment to be more volatile than output and 2) procyclicality to the opportunity cost of employment, consistent with Chodorow-Reich and Karabarbounis (2016).

[44] The contribution of labor supply shocks in jobless recoveries is consistent with Aaronson et al. (2004).

the actual path to the hypothetical one where hours per worker are constant.[45]

Figure 6 contrasts the actual values of total hours, hours per worker, and employment (solid lines) with the model counterfactual values (dashed lines).[46] The figure shows that adjustment in hours per worker has sizable effects on the recovery of total hours (up to 3.5 percentage points in the recovery of 1982). The overall effect on total hours comes from both a direct and an indirect effect. The direct effect accounts for the variation in total hours stemming from adjustments in hours per worker for a given level of employment. The indirect effect accounts for the impact that fluctuations in the intensive margin have on new matches (and thus employment) in response to aggregate shocks. As shown by figure 6, lack of adjustment along the intensive margin would have mitigated employment losses during recessions and resulted in quicker employment recoveries. We find that the volatility of employment drops by 13 percent over the sample in the counterfactual economy. Moreover, the standard deviation of total hours is 40 percent lower. Two-thirds of this drop is accounted for by the lack of adjustment in hours-per-worker while the remaining part depends on the indirect effect of the intensive margin on employment. These results imply that hours adjustment contributes positively to employment volatility during post-war U.S. recessions and recoveries.

What accounts for the importance of the indirect effect of hours per worker on employment? Figure 7 plots the differences in the historical decompositions of employment from the preferred and counterfactual models. As seen in the figure, investment-specific shocks account for most of the differences in employment dynamics in the two economies. Labor market shocks also are important.[47]

To understand the different transmission of these two shocks with and without the intensive-margin adjustment, we return to our impulse response analysis. Figure 5 plots the responses in the counterfactual economy with constant hours (dashed lines). An increase in investment-specific productivity remains expansionary in the counterfactual economy. However, the absence of hours adjustment implies a larger response of effective capital and a much lower response of total hours. Since this shock induces positive comovement between the labor margins, the expected present discounted value of new matches rises less in response to positive shocks when hours are

[45] Results are unaffected if hours per worker are held constant at the beginning of the trough of each recession (rather than at the beginning of the sample).

[46] Since total hours and employment are observables and there is no measurement error, the smoothed estimates of these variables from the two-sided Kalman filter, as well as hours per worker, perfectly match the data by construction.

[47] In particular, investment specific shocks account for large differences in the dynamics of the two economies in the recoveries of 1970, 1975 and 2001. Shocks to workers' bargaining power are more important in the recovery of 1991, while the lack of hours supply shocks dominates in 1982.

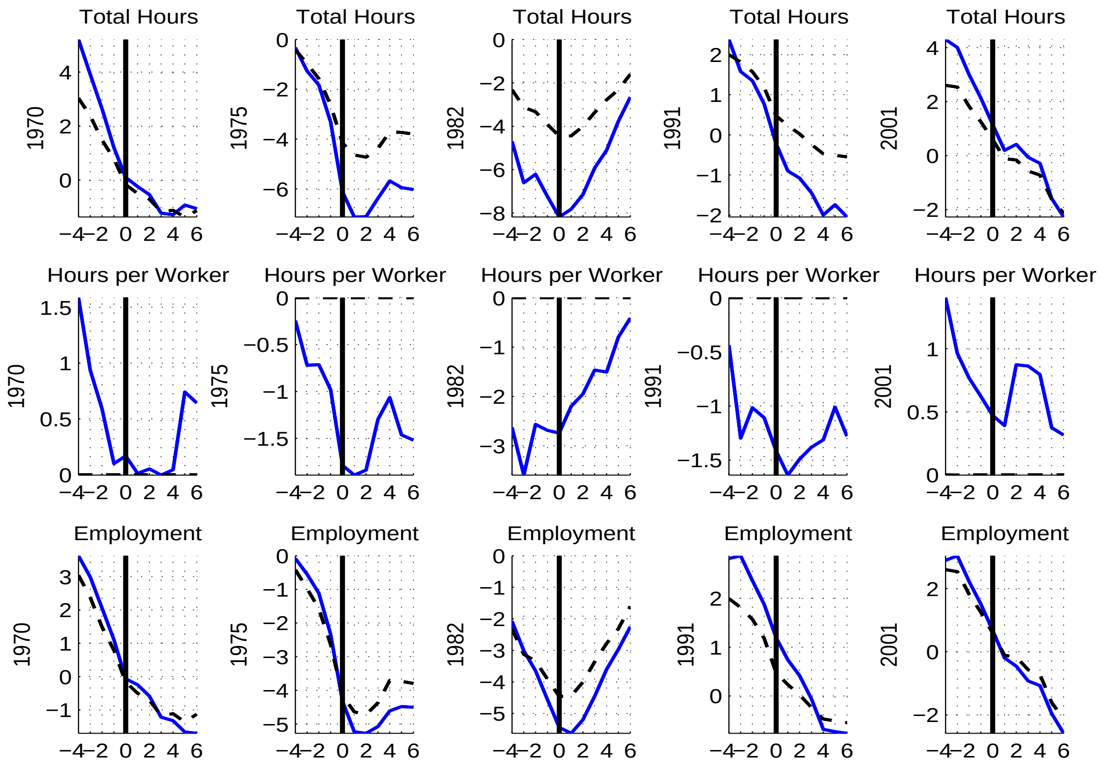

Figure 6. U.S. recoveries relative to GDP trough. Blue solid lines: preferred model. Black dashed lines: counterfactual with hours per worker constant

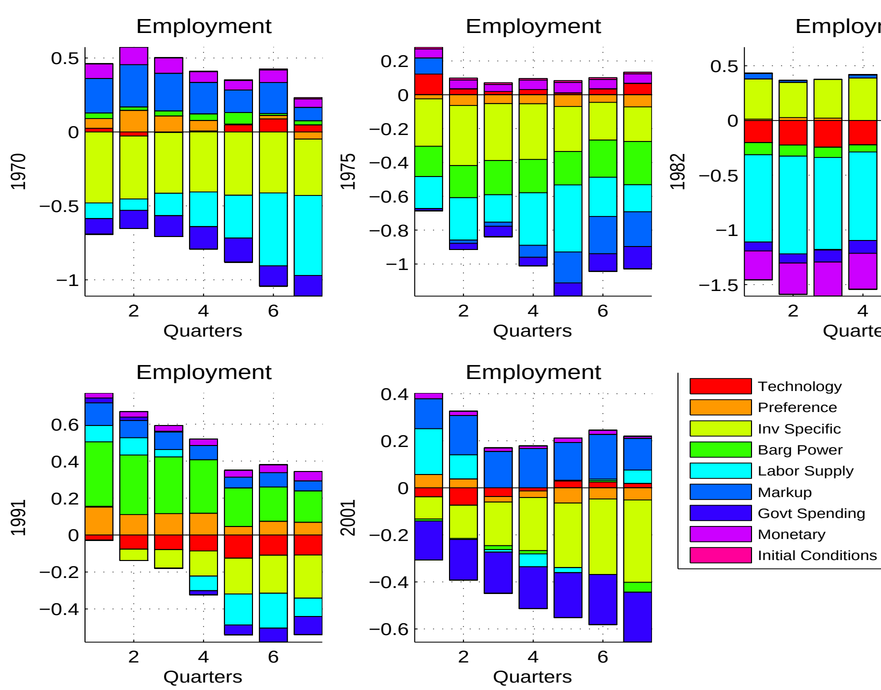

Figure 7. Differences between historical decompositions for employment in preferred model and counterfactual with hours per worker constant during U.S. recoveries.

constrained and do not increase. Moreover, achieving the same adjustment of total hours would require additional vacancy posting in the counterfactual economy, which is costly due to congestion externalities. All else equal, this decreases firms' incentives to adjust employment, mitigating employment's response. Accordingly, firms raise effective capital more to meet a given demand. Notice that, in general equilibrium, a second channel occurs through relative price adjustments. Higher demand for effective capital raises the rental rate of capital, giving an incentive to producers to substitute capital with labor (i.e., to hire more workers).[48] In the case of an exogenous increase in the workers' bargaining power, firms can no longer substitute away from the relatively cheaper labor input (hours per worker), leading employment to fall less than in the preferred model.

7 Sensitivity Analysis

We investigate the robustness of our results under several alternative specifications. The results of these robustness checks are summarized in table 3. For reference, the first two rows report the results of the baseline and preferred models, previously discussed. To understand how well the model accounts for the labor market variables, we report for each specification the shares of the variance of total hours attributed to hours per worker, employment, and their covariance. In addition, we report log marginal data densities and twice the natural logarithm of Bayes factors to provide an assessment of relative fit of models to the data, see section 5 for more discussion. In all robustness cases, the preferred model implies a substantially greater fit. We discuss each robustness case in turn.

The preferred model includes two additional features relative to the baseline, namely JR preferences and costly hours adjustment. We consider each extension separately in the rows labeled "Model w/o JR preferences" and "Model w/o costly hours adj." Although each feature individually improves the model's fit relative to the baseline, the inclusion of both, the "Preferred Model" row, provides the best fit. Omitting JR preferences reduces the model's ability to match the positive covariance between employment and hours per worker, as discussed in section 5.

[48]This feedback effect is stronger for shocks that are more persistent, since the present discounted value of job creation increases more in this case. In turn, the strength of the general equilibrium effect accounts for the responses to preference and markup shocks in figure 5, as these shocks have high estimated persistence.

Alternative Shocks

We estimate the baseline model with seven observables when the hours supply shock is included as opposed to the bargaining power shock. Hours supply shocks can potentially improve the model's fit with respect to labor market variables, as they directly affect the intensive labor margin. The total hours variance shares in this case are listed in row "7 obs, $\bar{h}$ shock" of table 2. For comparison, the estimates from the baseline model with seven observables is included for reference in row "7 obs, $\bar{\eta}$ shock." While the hours supply shock does ensure the model matches the covariance of employment and hours per worker, it does so with a counterfactually high volatility of hours per worker, as β_h's bands encompass higher values than β_L's bands.

Wage Data

We document the robustness of our results to the wage observable. Using U.S. micro data, Haefke et al. (2013) document that the wages of newly hired workers, unlike wages in ongoing relationships, are volatile and procyclical. In addition, our baseline wage observable is not restricted to earnings, as it includes employer contributions to employee-benefits (Justiniano et al., 2013). We address these issues as follows. We estimate a version of the preferred model in which three measures of the wage are simultaneously included in the observables. This strategy has been recently used by several papers in the estimation literature (see for instance Boivin and Giannoni (2006), Gali et al. (2011), and Justiniano et al. (2013)). The first is the measure described in section 4, which is the BLS' hourly compensation for the nonfarm business sector. The second measure is the BLS' average

Table 3: Robustness checks from Alternative Estimated Specifications.

		Log Marginal Data Density	2 ln(Bayes Factor) vs. Preferred	β_h	β_L	β_{cov}
CES Data				**0.18**	**0.51**	**0.31**
	Preferred Model	-1024	0	[0.13, 0.56]	[0.20, 0.71]	[-0.05, 0.44]
	Baseline Model	-1073	98	[0.16, 0.76]	[0.22, 0.89]	[-0.43, 0.37]
	Model w/o JR preferences	-1041	34	[0.13, 0.57]	[0.24, 0.83]	[-0.21, 0.41]
	Model w/o costly hours adj.	-1043	38	[0.14, 0.58]	[0.19, 0.57]	[-0.04, 0.43]
	Preferred Model, mix wage obs	-1332	0	[0.06, 0.56]	[0.22, 0.95]	[-0.28, 0.45]
	Baseline Model, mix wage obs	-1380	96	[0.09, 0.72]	[0.26, 1.12]	[-0.62, 0.39]
	7 obs, $\bar{\eta}$ shock	-1008	0	[0.03, 0.22]	[0.64, 1.21]	[-0.35, 0.25]
	7 obs, $\bar{h}$ shock	-1076	136	[0.18, 0.60]	[0.10, 0.50]	[0.16, 0.44]
CPS Data				**0.07**	**0.78**	**0.15**
	Preferred Model	-1152	0	[0.05, 0.30]	[0.31, 0.70]	[0.14, 0.45]
	Baseline Model	-1184	64	[0.11, 0.47]	[0.26, 0.78]	[-0.07, 0.43]
SW Data				**0.39**	**0.44**	**0.17**
	Preferred Model	-989	0	[0.14, 0.62]	[0.18, 0.67]	[-0.07, 0.42]
	Baseline Model	-1051	124	[0.20, 0.83]	[0.19, 0.80]	[-0.40, 0.36]

Note: Parenthesis denote 90 percent posterior intervals. Log marginal data densities calculated using Geweke's modified harmonic mean estimator; values are comparable conditional on observables, with different sets denoted by horizontal lines.

hourly earnings of production and nonsupervisory employees. The third measure is the quality adjusted wage series of Haefke et al. (2013), which adjusts for individual-level characteristics. We assume that each series represents an imperfect measure of the model wage according to:

$$\begin{bmatrix} \text{Comp Wage}_t \\ \text{Earn Wage}_t \\ \text{Quality Wage}_t \end{bmatrix} = \begin{bmatrix} \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \end{bmatrix} (\hat{w}_t - \hat{w}_{t-1} + \hat{g}_{At}) + \begin{bmatrix} e_{1t} \\ e_{2t} \\ e_{3t} \end{bmatrix}$$

where e_{it} for $i = 1, 2, 3$ denote *iid* observation errors.[49] Rows "Preferred Model, mix wage obs" and "Baseline Model, mix wage obs" of Table 3 display the total hours variance shares in this case. Again, the preferred model has a better fit, with bands well encompassing the data.

Alternative Labor Market Variables and Subsample Analysis

We check whether our results are sensitive to the labor market measures used for the estimation. We estimate the model using CPS labor market variables, as in Ramey (2012).[50] In this case, neither total hours nor employment are linearly detrended as it is less obvious the series exhibit a deterministic trend; the two variables are demeaned. Parameter estimates in this case are comparable to those in table 2. Bayes factors suggest strong preference for the preferred model as well. As shown in table 3, the posterior bands for the model's βs well-encompass their data counterparts. In addition, these results are robust to using the Smets and Wouters (2007) labor market observables for estimation, which are commonly employed in the DSGE estimation literature, as evidenced by the last rows of table 3.

Finally, our analysis of U.S. recoveries is robust to sub-sample estimation conditional on our observables. This experiment allows us to address how structural change in parameter estimates (in particular, those directly affecting labor market dynamics) contributes to the dynamics of hours and employment in post-war U.S. data (the results are available upon request). As is common practice in the literature, we split our original sample at the start of the so-called Great Moderation, estimating from 1965:1 to 1983:4 and 1984:1 to 2007:4.

[49]The priors for the Γ's are normal distributions centered at 1 with a standard deviation of 0.5. The priors for the standard deviations of the wage observation errors are inverse gamma distributions with mean of 0.1 and standard deviation of 1. Specifically, we use the median real wage of new hires corrected for fluctuations in all observable worker characteristics from Haefke et al. (2013). This series is not available for the full sample period, but the Kalman filter handles missing observations.

[50]See Appendix A for a description of the alternative labor market data.

8 Conclusions

We estimate a baseline search and matching model augmented with endogenous fluctuations in hours per worker and shocks that affect both margins of labor adjustment. We show that this baseline model is unable to replicate the correlation structure between aggregate macroeconomic series and labor market variables. Two proposed modifications reconcile the model with the data: adjustment costs to the intensive margin and a flexible parametrization of the strength of the short-run wealth effect on hours supply, as first introduced by Jaimovich and Rebelo (2009). We use the modified model to structurally assess the contribution of the intensive margin of labor adjustment to aggregate dynamics.

We find the contribution of hours per worker to total hours is quantitatively significant, with a notable component stemming from its indirect effect on employment adjustment. For instance, the standard deviation of total hours is 40 percent lower in the constant hours counterfactual relative to the estimated model. Two-thirds of this drop is accounted for by the lack of adjustment in hours-per-worker while the remaining part depends on the indirect effect of the intensive margin on employment.

While we estimate the model on U.S. data, our model introduces enough flexibility to allow the model to match a broad array of empirical covariances between hours per worker and employment, including potentially negative ones as observed in some European economies. Discerning the role of the intensive margin for other countries, as well the introduction and study of country-specific labor market policies, are important avenues for future research.

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