Investment-Specific Shocks and Cyclical Fluctuations in a Frictional Labor Market*

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Abstract

This paper studies the role of investment-specific shocks as an amplification mechanism in the labor market fluctuations. We first show evidence that suggests that when technological advances make equipment more expensive, not only investment and output decrease but also firms post fewer vacancies, hours worked are reduced and unemployment increases. Moreover, we study the quantitative impact of this type of shocks on the labor market by incorporating them into a Real Business Cycle model with search and matching frictions. We find that in our model these shocks have direct amplification effect on labor market fluctuations, increasing the volatility of the labor market variables between two and five times.

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1 Introduction

Real Business Cycle (RBC) theory stresses that neutral technology shocks are a major source of economic fluctuations. However, a main problem with this driving force is the need to incorporate unrealistic large shocks to reproduce some business cycle facts (see King and Rebelo, 1999, for a discussion). Similarly, studying the U.S. labor market behavior in a standard search and matching model, Shimer (2005) has shown that reasonable shocks to labor productivity do not help reproduce the cyclical fluctuations in relevant labor market outcomes such as vacancies and unemployment. This suggests that there exist other important sources of aggregate fluctuation beyond standard productivity shocks.

One natural alternative to neutral technology shocks is investment-specific technological change. Greenwood, Hercowitz, and Huffman (1988) are the first to study the quantitative implications for business cycle fluctuations of shocks to the marginal efficiency of investment. Their results suggest that this type of shocks may be important for the understanding of business cycles. More recently, Greenwood, Hercowitz, and Krusell (2000) investigate the quantitative importance of investment-specific technological change for postwar U.S. aggregate fluctuations. They find that this form of technological change accounts for about 30 percent of output fluctuations.

In a empirical study, Fisher (2006) shows that when neutral and investment-specific technology shocks are combined they account for 44 and 88 percent of the fluctuations in the U.S. output at business cycle frequencies before and after 1982, respectively. Similarly, both shocks account for 73 and 38 percent of hours' business cycle variation. Fisher claims that investment-specific shocks are responsible for most of these effects. Canova, López-Salido, and Michelacci (2007) and Ravn and Simonelli (2008) also find empirical evidence that this type of shocks are important for business cycle fluctuations not only in output but also in labor market indicators, such as vacancies, unemployment and hours worked.

In this paper we also provide empirical evidence from the postwar period in the U.S. showing a link between the relative price of new equipment and labor market outcomes. More in detail, the data suggests that when technological advances make new equipment less expensive, not only the investment in new equipment increases but also the number of vacancies and the number of hours worked, at least in the short run. Moreover, other labor market variables such as unemployment and job finding rate also seem to respond to this type of shocks.

These findings motivate our quantitative analysis. Specifically, we investigate the impact of investment-specific shocks on the labor market by incorporating them into an otherwise standard RBC model with labor search and matching frictions.

Besides the well known amplification effect of investment-specific shocks on output fluctuations, (for a detail discussion of the mechanisms at work see Greenwood, Hercowitz, and Huffman, 1988; Greenwood, Hercowitz, and Krusell, 2000) we find that they have an additional impact on the volatility of labor market variables through their indirect effect on labor productivity. For instance, a positive investment-specific shock has an expansionary effect on investment, increasing next-period capital stock. This increases marginal labor productivity in the future for a given level of the labor input, which foster job creation and reduces unemployment. This channel seems to be of quantitative importance. Our main result is that investment-specific shocks do help the model generate significant cyclical movements in key labor market variables such as unemployment and employment, generating around 80 percent of their observed volatility in the U.S. labor market. Moreover, the simulated standard deviation in hours per worker also increased but in a smaller magnitude than in employment. Despite this improvement, the model still shows relatively low variability in vacancies and job finding probability with standard deviations that are at most 40 percent as volatile as in the data.

We also consider the role of capital utilization and endogenous separations as

propagation and amplification mechanisms. Shapiro (1996) stresses the importance of capital utilization for studying business cycles. Using the workweek of capital as a measure of utilization, his paper documents that this is an important margin of adjustment in many U.S. manufacturing industries over the business cycle. Furthermore, he finds that there is little or no cyclical movement in productivity once capital utilization is taken into account, and concludes that the RBC literature “needs to focus on the sources of shocks other than those to aggregate productivity” (p. 118). In a previous work, Shapiro (1986) argues that since capital utilization (measured again as the workweek of capital) is essentially costless to adjust, it responds immediately to shocks. In fact, he finds that in response of shocks, the workweek of capital tends to overshoot to compensate for the slow and costly adjustment of the capital stock. In particular, shocks to the purchase price of capital and the rate of return have substantial effects on capital utilization. Our simulated results show that capital utilization has a stronger amplification mechanism over output than over the other variables, especially labor market variables. This is a somewhat intuitive result because the capital utilization margin works as a substitute for labor services.

Another important result is that endogenous separations amplify the labor market fluctuations, specially in unemployment and job separations. However, vacancies become countercyclical. Thus, the model fails to reproduce the downward-sloping Beveridge curve.

Our work is related to Michelacci and Lopez-Salido (2007) who also explore the effect of investment-specific technological advances on labor market outcomes. They consider a growth model where technological progress can be investment-specific or investment neutral. Moreover, the reallocation of workers is sluggish due to search frictions in the labor market. Their paper analyzes the dynamic response to permanent technology shocks when there are vintage-capital effects. In the model presented here we consider transitory technology shocks. In addition, unlike them, we assume

that neutral technological progress is entirely disembodied.

Hornstein, Krusell, and Violante (2007) also consider a vintage capital model with search and matching frictions. They propose a simple extension of the standard search model and find that, for a calibrated version of their model with investment cost shocks, unemployment and labor-market tightness are more volatile than in the standard model.

More closely related to our paper are De Bock (2007), and Faccini and Ortigueira (2009) who also study the implications of investment-specific technology shocks in business cycle model with search and matching frictions. Our model is somewhat similar to their models, especially to Faccini and Ortigueira's, but it differs in one important dimension: we introduce endogenous capital utilization into the model, which is a key variable through which technological shocks affect the labor market. Although several authors have extended the basic RBC model to incorporate this variable,¹ to our knowledge, this is the first attempt to explore its impact on frictional labor market.

While in De Bock (2007) investment-specific shocks do not generate amplification in labor market variables, in Faccini and Ortigueira (2009) the volatilities of vacancies and unemployment are multiplied by three when this type of shocks are introduced into the model. Their model with neutral and investment-specific shocks as well as endogenous hours worked is able to reproduce 23 and 42 percent of the observed standard deviations in unemployment and vacancies, respectively (see their table 8). Instead, our baseline model is able to reproduce 79 and 40 percent, in each case.

This paper is organized as follows: Section 2 explores the cyclical behavior of some relevant labor market outcomes and their relationship with fluctuations in the relative price of new equipments as a proxy of investment-specific technological shocks. Section 3 presents the model economy to be used for our quantitative analysis. In

¹King and Rebelo (1999), Kydland and Prescott (1988), and Greenwood, Hercowitz, and Huffman (1988), among others

Section 4 we calibrate our model and analyze the simulation results in Section 4.1. Finally, Section 5 presents the conclusions.

2 Relative price of investment and business cycle facts in the U.S. labor market

This section documents the cyclical behavior of the relative price of investment in new equipments as well as its relation to other relevant aggregate variables for the U.S. economy, which we describe below in detail. In particular, we focus our analysis on labor market variables.

In Subsection 2.2, we document the properties of the series following the standard practice in the business-cycle literature. We also examine the causal relations between the relative price of investment and labor market variables. Then, in Subsection 2.3, we look at the conditional correlations of VAR forecast errors at different horizons.

2.1 Data

The data on the relative price of new equipment, p_e , is taken from Michelacci and Lopez-Salido (2007). They use an annual series constructed by Cummins and Violante (2002), and convert it into quarterly data as in Fisher (2006) from 1955 to 2000. Unfortunately, there is no additionally data on p_e . More in detail, p_e is the quality-adjusted price of new equipment divided by the Consumer Price Index.²

In our empirical analysis, we also look at total output and investment, which we denote y and i , respectively. As it is standard, output is the real gross domestic product, and investment is the real gross private domestic investment in equipment and software. Both are taken from the National Income and Product Accounts (NIPA)

²In a more recent study, Canova, López-Salido, and Michelacci (2007) show that the empirical results are not sensitive to the choice of deflator.

and seasonally adjusted by the U.S. Bureau of Economic Analysis (BEA).

Another variable in our analysis is the workweek of capital which we use as a proxy of capital utilization, h . Quarterly data on the workweek of capital is taken from Orr (1989). Unfortunately this indicator is only available until 1984.

Among the labor market variables we have vacancies and the unemployment rate. Data on vacancies, v , is obtained from the seasonally adjusted help-wanted advertising index, constructed by the Conference Board. The seasonally adjusted unemployment rate, u , is measured by the Bureau of Labor Statistics (BLS) from the Current Population Survey (CPS). Both variables are quarterly average of monthly data.

The job finding rate, j , and separation rate, ρ , correspond to quarterly averages of monthly rates and they are constructed by Robert Shimer from seasonally adjusted employment, unemployment, and mean unemployment duration, all computed by the BLS from the CPS.³

Hours per worker, l , are measured as the total private average weekly hours of production workers. Total hours, nl , correspond to the index of aggregate weekly hours in the private sector, which are the product of average weekly hours, l , and nonsupervisory worker employment, n . Both l and nl , as well as employment, n , are seasonally adjusted series constructed by the BLS from the Current Employment Statistics (CES). Hours worked are only available since 1964.

Labor productivity y/n is seasonally adjusted real average output per person in the non-farm business sector, constructed by the BLS from the NIPA and the CES. Finally, the wage w is real hourly compensation index in the non-farm business sector also constructed by the BLS from NIPA and CES.

³These two rates are calculated considering a two-state model (employed or unemployed) for workers. For additional details, please see Shimer (2007) and his webpage <http://robert.shimer.googlepages.com/flows>

2.2 Unconditional correlations and causality

Table 1 shows statistics describing the cyclical behavior of relevant variables related to the relative price of investment. It includes measures of cyclical volatility as well as correlations with p_e at leads and lags of up to four quarters. We obtain the cyclical component of the series by applying the Hodrick-Prescott (HP) filter, with smoothing parameter 1600, to data that have been logged. In this subsection, when we refer to some variable x , we are actually referring to its cyclical component as we just defined.

There is a negative contemporaneous correlation of -0.436 between p_e and y . Moreover, we found evidence that p_e leads the cyclical behavior of y by about two quarters given that their correlation reaches a maximum (in absolute value) at that point. Moreover, p_e is almost exactly as volatile as y with a standard deviation of 1.6% with respect to its trend.

The evidence from the postwar period in the U.S. suggests an important link between the relative price of new equipment and investment at both low and high frequency as it has been emphasized by authors like Greenwood, Hercowitz, and Krusell (2000). We also find that there is negative comovement between p_e and i at business cycle frequency with a correlation of -0.444. Moreover, there is a negative correlation between p_e and capital utilization h with a maximum correlation of -0.440 when p_e is leading by three quarters.

We now look at the relationship between p_e and labor market variables. We observe a negative correlation with vacancies v (-0.430) and employment n (-0.474), with p_e slightly leading v by no more than a quarter at the most. As expected then, p_e and the unemployment rate u are positively correlated (0.415). We also find a slightly positive contemporaneous correlation of 0.112 with the job separation rate ρ , which lags about two to three quarters behind p_e . Furthermore, the job finding rate j is negatively correlated with p_e (-0.418), and shows no lag or lead relative to the latter.

Table 1: RELATIVE VOLATILITY AND CROSS-CORRELATION OF RELATIVE PRICE OF INVESTMENT AND OTHER RELEVANT VARIABLES: U.S. QUARTERLY DATA 1955-2000

	$p_e(+4)$	$p_e(+3)$	$p_e(+2)$	$p_e(+1)$	p_e	$p_e(-1)$	$p_e(-2)$	$p_e(-3)$	$p_e(-4)$
n (.629)	-.212	-.310	-.398	-.461	-.474	-.446	-.344	-.199	-.053
l (.252)	-.330	-.400	-.438	-.441	-.355	-.179	.023	.193	.288
nl (1.174)	-.362	-.474	-.566	-.623	-.603	-.481	-.295	-.093	.078
u (6.918)	.210	.297	.373	.421	.415	.361	.253	.125	.008
v (8.383)	-.262	-.339	-.408	-.444	-.430	-.368	-.257	-.119	.016
j (4.623)	-.191	-.284	-.366	-.417	-.418	-.368	-.245	-.112	.009
ρ (2.912)	.267	.278	.280	.233	.112	-.002	-.093	-.124	-.124
w (.558)	-.212	-.155	-.093	-.025	.023	.013	-.004	-.007	-.010
y/n (.849)	-.462	-.447	-.383	-.279	-.151	-.008	.150	.280	.359
i (3.257)	-.253	-.328	-.382	-.425	-.444	-.424	-.330	-.191	-.043
h (1.517)	-.398	-.440	-.400	-.292	-.185	-.074	.011	.112	.169
y (.981)	-.411	-.472	-.499	-.487	-.436	-.340	-.193	-.035	.098

Note: Standard deviations relative to $\sigma(p_e) = 0.016$ in parentheses.

Table 1 also shows a negative correlation with both hours per worker l (-0.355) and total hours nl (-0.603). Moreover, there is some evidence that p_e leads both.

Finally, there is a negative correlation between labor productivity y/n and p_e , with a maximum correlation of -0.462 when p_e leads by four quarters. However, we also observe that the sign of this correlation switches from a negative to a positive value. Similar changes in the sign of the correlation coefficients are observed with respect to l and ρ . Finally, we do not observe a significant correlation between p_e and wages w .

In summary, these unconditional correlations seem to indicate that when new equipment becomes less expensive not only investment and capital utilization increase but also firms post more vacancies and less jobs are destroyed. Thus, it becomes easier for unemployed workers to find jobs which implies a higher job finding rate. As a result, unemployment falls. Moreover, hours per worker tend to increase which, together with the rise in employment, implies a boost of total hours. This increase in hours as well as in capital utilization has a positive impact on total output. This effect on output is big enough to make output per worker (i.e., labor productivity) increase as well.

This evidence presented thus far does not tell us anything about the role of shocks to the relative price of new equipment as a driving force of the U.S. business cycle and, in particular, labor market fluctuations, which is the main goal of this paper. To that end we now look at the causal relations between p_e and our labor market variables. Thus, we perform a Granger causality test by estimating the following bivariate VAR with lag-length k :⁴

$$\begin{pmatrix} x_{1t} \\ x_{2t} \end{pmatrix} = \sum_{i=1}^k \begin{pmatrix} \alpha_{11,i} & \alpha_{12,i} \\ \alpha_{21,i} & \alpha_{22,i} \end{pmatrix} \begin{pmatrix} x_{1,t-i} \\ x_{2,t-i} \end{pmatrix} + \begin{pmatrix} v_{1t} \\ v_{2t} \end{pmatrix},$$

⁴The optimal lag order is chosen by minimizing the Akaike Info Criterion.

where x_1 and x_2 are the cyclical component of p_e and one of the other variables, respectively. In general, a variable $x_{1,t}$ is said to be Granger causing $x_{2,t}$ when a prediction of $x_{2,t}$ on the basis of its past history can be improved by further taking into account lags of $x_{1,t}$. In other words, x_{1t} is not Granger causal for x_{2t} (i.e., $x_{1t} \sim GC x_{2t}$) if and only if

$$\alpha_{21,i} = 0, \forall i = 1, 2, \dots, k.$$

The first two columns of Table 2 show the p -values associated to the F -distribution and indicate the probability of a false rejection of the null hypothesis ($x_{1t} \sim GC x_{2t}$, and viceversa). Thus, at the 5% significance level, p -values lower than 0.05 are indicative of Granger-causality.

Table 2: Granger and instantaneous causality tests among the relative price of new equipment and the labor market variables. p -values

Variable x_{2t}	$x_{2t} \sim GC p_e$	$p_e \sim GC x_{2t}$	Not IC between p_e and x_{2t}
n	.076	.004	.161
l	.651	.001	.001
nl	.529	.000	.000
u	.141	.049	.087
v	.051	.012	.003
j	.266	.006	.077
ρ	.004	.159	.796
w	.205	.938	.073
y/n	.007	.003	.285

Note: Results from the estimated Granger causality tests. $\sim GC$ means does not Granger cause. IC means instantaneous causality. The causality tests are performed using the software JMulTi, freely available at the web page <http://www.jmulti.de>.

As displayed in Table 2, the Granger causality tests suggest that p_e is connected with all the labor market variables except w . There is one-way causal linkage from the relative price of new equipment to employment, hours worked, unemployment, vancancies and the job finding probability, and one-way causal linkage from the job separation rate to p_e . Finally, there is a bidirectional link between the relative price

of investment and labor productivity.

In the standard matching and search model, see Pissarides (2000), vacancies tends to immediately adjust to its new equilibrium when there is a shock to the system. To discern if v respond immediately to investment specific shocks, the Instantaneous Causality Test (IC) following Lutkepohl (1991) can be performed. This test is characterized by nonzero correlation of v_{1t} and v_{2t} , in which case the null hypothesis

$$H_0 : E(v_{1t}v'_{2t}) = 0,$$

is tested against the alternative of nonzero covariance between the two error vectors. Thus, a rejection of H_0 implies evidence in the direction of instantaneous causality (IC) between p_e and x_2 , although the test is not able to identify the causal source.⁵ The last column of Table 2 confirms the presence of an instantaneous causality between p_e and v . Hence, there is evidence suggesting that vacancies adjust immediately in response to shocks to the relative price of investment.

2.3 Conditional correlations

One problem with focusing on unconditional correlations is that they are defined only for stationary variables. This involve rendering the data stationary through the HP filter, which in turns has potentially significant effects on the unconditional correlation coefficients (for more details, see Canova, 1998). In addition, looking only at unconditional correlations implies some loss of information regarding the dynamics of comovement of variables.

To assess the robustness of last results, we employ a recently developed methodology suggested by den Haan (2000). This new approach is based on vector autoregression (VAR) methodology and does not require pre-filtering the data since it can

⁵The test statistic is based on the usual Wald principles with an asymptotic χ^2 -distribution.

accommodate both integrated and stationary variables. It yields a set of correlation coefficients of VAR forecast errors at different horizons. Basically, from a set of estimated bivariate VARs between the relative price of investment and the rest of the labor market variables considered in Table 1, we construct time series for the forecast errors using the difference between subsequent realizations and their forecasts. These time series are then used to generate covariance and correlation coefficients.

Table 3: CORRELATION COEFFICIENT BETWEEN k -QUARTER AHEAD FORECAST ERRORS OF RELATIVE OF INVESTMENT AND LABOR MARKET VARIABLES

Horizon	u	n	l	nl	v	j	ρ	w	y/n
1	.267*	-.204*	-.252*	-.376*	-.286*	-.222*	.126	.061	-.036
2	.393*	-.369*	-.305*	-.453*	-.430*	-.365*	.201*	.017	-.080
3	.487*	-.453*	-.334*	-.496*	-.525*	-.433*	.254*	-.028	-.128
4	.547*	-.508*	-.333*	-.505*	-.564*	-.488*	.290*	-.080	-.178
5	.589*	-.537*	-.311*	-.504*	-.585*	-.512*	.317*	-.134	-.229
6	.620*	-.546*	-.285*	-.501*	-.609*	-.517*	.336*	-.188	-.280*
7	.647*	-.539*	-.267*	-.502*	-.626*	-.506*	.351*	-.237	-.327*
8	.667*	-.521*	-.261*	-.513*	-.634*	-.484*	.362*	-.280	-.369*
12	.707*	-.419*	-.297*	-.518*	-.601*	-.379*	.384*	-.374*	-.467*
16	.716*	-.351*	-.295*	-.540*	-.556*	-.324*	.389*	-.409*	-.498*
20	.717*	-.320*	-.299*	-.539*	-.543*	-.294*	.390*	-.429*	-.509*

Note: * means statically significant at 5% level.

The series are expressed in logs but without applying the HP filter. The VARs were estimated without imposing the unit-root restriction and considering linear and quadratic trend when necessary.⁶ The lag length in the VAR, as well as the deterministic components were chosen using the Akaike Information Criterion (AIC). Table 3 summarizes the correlation coefficients for a forecast horizon of up to five years, a period equivalent to the average duration of the U.S. business cycle during the period 1854-2001. Bootstrapped standard errors based on 1000 replications were used

⁶The Matlab program was writing by Steve Sumner and can be download at den Haan's web page <http://faculty.london.edu/wdenhaan/>.

to construct 95 percent confidence bands and standard errors. Clearly, we observe that the forecast error correlation coefficients are consistent with the unconditional correlations observed in Table 1. The most important result from this exercise is that the sign of the correlation between p_e and the rest of the labor market variables remains unchanged, except for w , during the length of the business cycle, suggesting an stable and significative relationship between the relative price of investment and these variables.

3 The model

3.1 The representative firm and the frictional labor market

We assume that there exists a competitive representative firm which uses labor services L and capital K to produce output Y with a constant-return-to-scale (CRS) production function $e^\zeta F(Kh, \Phi L) = e^\zeta (Kh)^\alpha (\Phi L)^{1-\alpha}$, where ζ is an aggregate technology shock, h denotes the rate of capital utilization, Φ represents labor-augmenting technological change, and $\alpha \in (0, 1)$. The stochastic variable ζ follows a first-order autoregressive process of the form

$$\zeta' = \rho_\zeta \zeta + \nu'_\zeta, \quad (1)$$

with $|\rho_\zeta| < 1$, and $\nu_\zeta \sim N(0, \sigma_\zeta)$. The productivity parameter Φ is assumed to grow at a constant rate γ_ϕ^* , which implies that $\Phi' = \exp(\gamma_\phi^*)\Phi$.

Due to CRS, we can write average output per efficiency unit of labor as $f(kh) = F(kh, 1)$, where $k = K/\Phi L$.

The representative firm owns the capital and therefore makes the capital accumulation decisions. Investment i is subject to a random transformation rate Υ so that

the firm accumulates $i\Upsilon$ units of capital for next period.⁷ We assume that Υ grows at a stochastic rate γ_v , which follows the AR(1) process

$$\gamma'_v = (1 - \rho_v)\gamma_v^* + \rho_v\gamma_v + \nu'_v, \quad (2)$$

with $|\rho_v| < 1$, and $\nu_v \sim N(0, \sigma_v)$. Thus, let

$$\Upsilon' = \exp(\gamma'_v)\Upsilon. \quad (3)$$

Capital also depreciates each period. As in Greenwood, Hercowitz, and Krusell (2000), the rate of depreciation depends on the capital utilization h , and takes the following functional form

$$\delta(h) = \frac{\xi}{\omega} h^\omega, \quad (4)$$

with $\omega > 1$, and $\xi > 0$.

Thus, the law of motion for the capital stock is

$$K' = (1 - \delta(h))K + i\Upsilon. \quad (5)$$

At the beginning of each period, the firm has a large number of matched workers M with which it could potentially establish (or continue) an employment relationship. Before production takes place, each matched worker draws an idiosyncratic labor-augmenting productivity level z from distribution $\Omega(z)$. We assume that z is i.i.d. across time and log-normally distributed $LN(0, \sigma_z)$. After the z 's are drawn, the firm breaks non-profitable matches. In particular, the firm chooses a threshold $\tilde{z}$ such

⁷An interpretation for this shock is that physical investment measured in consumption units, i , is enhanced by a quality index, Υ , which can be captured by the price index of consumption goods relative to the quality-adjusted price index for investment goods (i.e., the inverse of p_e). In other words, $i\Upsilon$ stands for investment measured in efficiency units. The improvement in the quality of capital goods reflected in higher values of Υ (the relative price of investment goods falls) is the driving force behind the investment-specific technological change.

that matches with $z < \tilde{z}$ are severed.⁸ Therefore, the firm's employment level can be approximated by

$$N = M(1 - \Omega(\tilde{z})). \quad (6)$$

Labor services L not only depend on N and the distribution of the productivity shock z but also on hours per worker l . We assume that l as well as wages w are determined through individual bargaining between each worker and the firm and, in principle, are function of z . Thus, labor services are given by

$$L = N \int_{\tilde{z}}^{\infty} z l(\cdot, z) d\tilde{\Omega}(z), \quad (7)$$

where $\tilde{\Omega}(z) \equiv \Omega(z|z \geq \tilde{z})$. Accordingly, the firm's wage bill is

$$W = N \int_{\tilde{z}}^{\infty} w(\cdot, z) d\tilde{\Omega}(z), \quad (8)$$

Our representative firm also posts job vacancies v every period. Each vacancy has a cost $\kappa\Gamma$, where κ is a constant and Γ denotes output trend.⁹ Moreover, each vacancy meets an unemployed worker with probability $\mu(\bar{u}, \bar{v})/\bar{v}$, where $\mu(\cdot, \cdot)$ is a CRS matching function that depends on the unemployment rate $\bar{u}$ and aggregate vacancies posted $\bar{v}$. In particular, we assume that

$$\mu(\bar{u}, \bar{v}) = \left(\frac{\bar{v}^\varphi}{1 + (\bar{v}/\bar{u})^\varphi} \right)^{1/\varphi}, \quad \varphi > 0. \quad (9)$$

The CRS assumption on the matching function implies that the probability of the firm meeting an unemployed worker only depends on the labor market tightness $\theta = \bar{v}/\bar{u}$. Thus, we will let $q(\theta) = \mu(\bar{u}, \bar{v})/\bar{v}$.¹⁰ Notice that the probability of a worker

⁸We guarantee that some necessary conditions are satisfied such that $\tilde{z}$ exists. See Appendix.

⁹This assumption is important to guarantee that the model has balanced growth path.

¹⁰An advantage of the functional form for the matching function above, as pointed out by den Haan, Ramey, and Watson (2000) who also use the same specification, is that the matching probabilities are bounded between 0 and 1 as opposed to a Cobb-Douglas form. This facilitates the

meeting a vacancy is $\mu(\bar{u}, \bar{v})/\bar{u} = \theta q(\theta)$ and, therefore, the job finding probability is $j(\theta, \tilde{z}) = \theta q(\theta)(1 - \Omega(\tilde{z}))$.

At the end of each period, a fraction $\bar{\rho}$ of employed workers N will be terminated exogenously. Therefore, the firm will have

$$M' = (1 - \bar{\rho})N + q(\theta)v \quad (10)$$

matched workers next period. Thus, the probability that a match does not survive by next period (i.e., separation probability) is

$$\rho(\tilde{z}) = \Omega(\tilde{z}) + \bar{\rho}(1 - \Omega(\tilde{z})). \quad (11)$$

The representative firm's problem is then to choose how intensively to use its capital h , the cutoff idiosyncratic productivity level $\tilde{z}$, next-period capital stock K' , and how many job vacancies v to post in order to maximize the value of the firm, given its current state (K, M) and the aggregate state of the economy $(\bar{A}, \bar{K}, \bar{M}, \zeta, \Upsilon)$, where $\bar{A}$ is aggregate households' wealth.

Strictly speaking, we assume that the economy has a perfect capital rental market, and that the representative firm also decides how much capital to use in its own production process and how much capital to rent out to “other” firms at a given rental rate r . However, in equilibrium, r is such that the firm ends up using exactly its entire own capital stock. That is, for any given h and L ,

$$r = \Upsilon e^{\zeta} h F_K(Kh, \Phi L), \quad (12)$$

where F_K denotes the derivative with respect to the first argument $\partial F(X, L)/\partial X$. For simplicity, we will formulate the firm's problem abstracting from this decision.¹¹

numerical solution of the model since truncations are not needed.

¹¹An alternative, equivalent environment is one where firms do not own capital and rent it from

Note that, given that Υ and Φ both have trend, the capital stock and output are non-stationary random variables. The Cobb-Douglas technology implies that the trend of output grows at rate $\gamma_y = (1 - \alpha)\gamma_\phi^* + \alpha\gamma_k$, where $\gamma_k = \gamma_v + \gamma_y$ is the growth rate of the capital stock trend. As a result, the growth rate of capital and output along the (stochastic) balance growth path (BGP) are

$$\gamma_k = \gamma_\phi^* + (1/1 - \alpha)\gamma_v, \quad (13)$$

$$\gamma_y = \gamma_\phi^* + (\alpha/1 - \alpha)\gamma_v. \quad (14)$$

Let us define the trend of output as well as investment as $\Gamma' = \exp(\gamma'_y)\Gamma$. Similarly, let the trend of capital stock be $\Gamma'_k = \exp(\gamma'_k)\Gamma_k$. Now we define the stationary counterpart of output, investment and capital as $\hat{Y} = Y/\Gamma_{-1}$, $\hat{i} = i/\Gamma_{-1}$ and $\hat{K} = K/\Gamma_{k,-1}$, respectively.¹² Now we can write

$$\hat{Y} = e^\zeta (\hat{K}h)^\alpha (\hat{\Phi}L)^{1-\alpha}, \quad (15)$$

where $\hat{\Phi} = \Phi\Gamma_{k,-1}^{\alpha/(1-\alpha)}/\Gamma_{-1}^{1/(1-\alpha)}$ is a constant which we normalize to 1 from now on.

Furthermore, the law of motion of capital (5) can be written as

$$\hat{i} = \hat{K}'e^{\gamma_y} - (1 - \delta(h))\hat{K}/e^{\gamma_v}. \quad (16)$$

Since wages must grow at the same rate as output along the BGP, we define

$$\hat{W} = N \int_{\tilde{z}}^{\infty} \hat{w}(\cdot, z) d\tilde{\Omega}(z), \quad (17)$$

where $\hat{w}(\cdot, z) = w(\cdot, z)/\Gamma_{-1}$.

households who are the ones making the investment decisions.

¹²Notice that we detrend these non-stationary variables using their previous period trend (e.g., Γ_{-1} in the case of output). This ensures that the stationary version of the firm's problem is well defined. That is, the firm knows $\hat{K}'$ when it chooses K' .

Notice that variables such as v , N , M , l , $\tilde{z}$, and h are stationary variables. Therefore, they do not need to be detrended.

The firm's dynamic programming problem, in normalized form, can be written as follows,

$$\begin{aligned} \Pi(s_f, \bar{s}) = \max_{h, \tilde{z}, \hat{K}', v} & \left\{ \hat{Y} - \hat{W} - e^{\gamma_y} \hat{K}' + \frac{1 - \delta(h)}{e^{\gamma_v}} \hat{K} - e^{\gamma_y} \kappa v + E[Q(\bar{s}) e^{\gamma_y} \Pi(s'_f, \bar{s}') | \bar{s}] \right\} \quad (18) \\ \text{s.t.} \quad & (4), (6), (7), (9), (10), (14), (15), (17), \\ & \theta = \Theta(\bar{s}), \quad \bar{s}' = G_s(\bar{s}), \end{aligned}$$

where $s_f = (\hat{K}, M)$ is the firm's state vector, $\bar{s} = (\hat{A}, \hat{K}, \bar{M}, \zeta, \gamma_v)$ is the aggregate state vector, $Q(\bar{s})$ is the current price of next-period consumption, $\Theta(\bar{s})$ represents the aggregate policy rule for θ , and G_s is the aggregate law of motion for $\bar{s}$.¹³ We assume that the firm simultaneously bargains with its workers and chooses $\{h, \tilde{z}, \hat{K}', v\}$.

The solution of the firm's dynamic programming problem yields optimal policy rules $g_h(s_f, \bar{s}) = h$, $g_z(s_f, \bar{s}) = \tilde{z}$, $g_K(s_f, \bar{s}) = \hat{K}'$, and $g_v(s_f, \bar{s}) = v$.

We can obtain these policy rules by solving the system of equations formed by the following first-order optimality conditions,

$$\hat{K}' : \quad 1 = E[Q(\bar{s}) \Pi_K(s'_f, \bar{s}') | \bar{s}], \quad (19)$$

$$v : \quad \kappa = q(\theta) E[Q(\bar{s}) \Pi_M(s'_f, \bar{s}') | \bar{s}], \quad (20)$$

$$h : \quad \delta'(h) = e^{\zeta + \gamma_v} F_K(\hat{K}h, L), \quad (21)$$

$$\begin{aligned} \tilde{z} : \quad \hat{w}(\cdot, \tilde{z}) = & \left[\tilde{z} l(\cdot, \tilde{z}) + N \int_{\tilde{z}}^{\infty} z \frac{\partial l(\cdot, z)}{\partial N} d\tilde{\Omega}(z) \right] e^{\zeta} F_L(\hat{K}h, L) \\ & - N \int_{\tilde{z}}^{\infty} \frac{\partial \hat{w}(\cdot, z)}{\partial N} d\tilde{\Omega}(z) + (1 - \bar{\rho}) E[Q(\bar{s}) e^{\gamma_y} \Pi_M(s'_f, \bar{s}') | \bar{s}], \end{aligned} \quad (22)$$

¹³Function G_s includes aggregate law of motions $G_A(\bar{s})$, $G_K(\bar{s})$, $G_M(\bar{s})$, and equations (1)-(2).

where

$$\Pi_K(s_f, \bar{s}) = e^\zeta h F_K(\hat{K}h, L) + (1 - \delta(h))/e^{\gamma_v}, \quad (23)$$

$$\begin{aligned} \Pi_M(s_f, \bar{s}) &= e^\zeta F_L(\hat{K}h, L) \int_{\tilde{z}}^\infty z \left[l(\cdot, z) + N \frac{\partial l(\cdot, z)}{\partial N} \right] d\Omega(z) \\ &\quad - \int_{\tilde{z}}^\infty \left[\hat{w}(\cdot, z) + N \frac{\partial \hat{w}(\cdot, z)}{\partial N} \right] d\Omega(z) + \frac{e^{\gamma_y} \kappa (1 - \bar{\rho}) (1 - \Omega(\tilde{z}))}{q(\theta)}. \end{aligned} \quad (24)$$

Condition (19) governs the accumulation of capital, equation (20) is the job creation condition, expression (21) determines the rate of capital utilization, and equation (22) is the job destruction condition. By substituting (20) into (22) and using the Cobb-Douglas production function assumption, we can rewrite the job destruction condition as

$$\begin{aligned} \hat{w}(\cdot, \tilde{z}) &= (1 - \alpha) e^\zeta f(\hat{k}h) \tilde{z} l(\cdot, \tilde{z}) + \frac{e^{\gamma_y} \kappa (1 - \bar{\rho})}{q(\theta)} \\ &\quad - N \int_{\tilde{z}}^\infty \left[\frac{\partial \hat{w}(\cdot, z)}{\partial N} - z \frac{\partial l(\cdot, z)}{\partial N} (1 - \alpha) e^\zeta f(\hat{k}h) \right] d\tilde{\Omega}(z), \end{aligned} \quad (25)$$

where $\hat{k} = \hat{K}/L$. The right hand side of equation (25) describes the losses of terminating such a worker net of its indirect impact on the individual wage-hours bargaining. Alternatively, it represents the marginal value of that worker. The first term on the right corresponds to lost output whereas the second term constitutes the expected loss for not having this marginal worker next period. The third term reflects the change in the wage bill and total output as a result of the impact on the wage-hours negotiations of laying off that marginal worker, which will become clear below. The firm terminates matches up to the point when is no longer profitable doing so. That is, when the worker's wage and her marginal value are equal.¹⁴

An useful result from the firm's problem is that the optimal amount of effective capital per efficiency unit of labor ($\hat{k}h$) depends only on the aggregate state $\bar{s}$.

¹⁴See Appendix for a discussion on the existence of $\tilde{z}$.

To see that, it is enough to look at optimality conditions (12) on the BGP (i.e., $e^{\zeta+\gamma\nu}hf'(\hat{k}h) = r$) and (21). By substituting the former into the latter, we obtain

$$h\delta'(h) = r.$$

This implies that h only depends on r , which in turn is only a function of the aggregate state $\bar{s}$. Hence, from (12), we conclude that so does $\hat{k}$.

3.2 Households

The economy is populated by a large number I of workers-consumers. Each worker may be either employed or searching for a job. Employed workers earn a wage w and work l hours.

As in Merz (1995) and Andolfatto (1996), we assume that there exists a perfect insurance market, and that all agents are ex-ante identical before employment status are revealed at the beginning of the initial period. Therefore there is a representative household who owns stock in the firm of value A (its wealth), and has a fraction m members matched to firms at the beginning of the current period. Its problem is to choose current per capita consumption c and per capita next-period wealth a' to maximize its lifetime utility.

We assume that each household member has instantaneous CES utility over consumption and leisure. We also assume that there is a fixed disutility b of working regardless of the number of hours worked. This can also be interpreted as the utility value of being unemployed. Thus, the instantaneous utility function takes the following form

$$\frac{[c^\psi(1-l)^{1-\psi}]^{1-\sigma}}{1-\sigma} - \mathbb{I}_{\{l>0\}}\Gamma^{\psi(1-\sigma)}b,$$

where $\mathbb{I}_{\{l>0\}}$ is an indicator function equal to 1 if the worker is employed (i.e. $l > 0$).

Formally, the (normalized) household's problem can be expressed recursively as

follows

$$\begin{aligned}
\mathcal{V}(s_h, \bar{s}) = \max_{\hat{c}, \hat{a}'} & \left\{ \frac{\hat{c}^{\psi(1-\sigma)} \left[n \int_{\tilde{z}_h}^{\infty} (1 - l(\cdot, z))^{\psi(1-\sigma)} d\tilde{\Omega}(z) + u \right]}{1 - \sigma} - e^{\gamma_y} b n \right. \\
& \left. + \beta e^{\gamma_y \psi(1-\sigma)} E[\mathcal{V}(s'_h, \bar{s}') | \bar{s}] \right\} \quad (26) \\
\text{s.t. } \quad & \hat{c} + Q(\bar{s}) e^{\gamma_y} \hat{a}' = n \int_{\tilde{z}_h}^{\infty} \hat{w}(\cdot, z) d\tilde{\Omega}(z) + \hat{a}, \\
& n = m(1 - \Omega(\tilde{z}_h)), \quad u = 1 - n, \\
& m' = n(1 - \bar{\rho}) + \theta q(\theta) u, \\
& \bar{s}' = G_s(\bar{s}), \quad \theta = \Theta(\bar{s}), \quad \tilde{z}_h = \tilde{Z}(\bar{s}),
\end{aligned}$$

where $s_h = (\hat{a}, m)$ is the household's state vector, $\beta \in (0, 1)$ is the discount factor, $\tilde{Z}(\bar{s})$ is the aggregate policy rule for the cutoff productivity $\tilde{z}$, and $\hat{a} = a/\Gamma_{-1}$ and $\hat{c} = c/\Gamma_{-1}$ are the detrended counterparts of wealth and consumption. The solution to this problem yields policy rules $g_c(s_f, \bar{s}) = \hat{c}$ and $g_a(s_f, \bar{s}) = \hat{a}'$.

The optimality conditions of the representative consumer's problem are

$$\hat{c}: \quad \lambda = \psi \hat{c}^{\psi(1-\sigma)-1} \left[n \int_{\tilde{z}}^{\infty} (1 - l(\cdot, z))^{\psi(1-\sigma)} d\tilde{\Omega}(z) + u \right], \quad (27)$$

$$\hat{a}': \quad \lambda Q(\bar{s}) e^{\gamma_y} = \beta e^{\gamma_y \psi(1-\sigma)} E[\mathcal{V}_a(s'_h, \bar{s}') | \bar{s}], \quad (28)$$

where λ is the Lagrange multiplier associated with the consumer's budget constraint, and

$$\mathcal{V}_a(s'_h, \bar{s}') = \lambda'. \quad (29)$$

Thus, we obtain that the current price of tomorrow's consumption satisfies

$$Q(\bar{s}) = \beta e^{\gamma_y(\psi(1-\sigma)-1)} E[\lambda'/\lambda]. \quad (30)$$

3.3 Wage-hours bargaining

Wages and hours are determined through Nash bargaining between the firm and each individual worker where they split the total surplus generated by that specific employment relationship. That implies that each worker is effectively the marginal worker, whose productivity depends on N . Thus, the relevant surplus depends on the marginal value of a job.¹⁵ Since each particular job is matched with a particular worker, its marginal value depends on the match-specific productivity $z_i \geq \tilde{z}$. Thus, in normalized form, it is equal to

$$\begin{aligned} \mathcal{W}^J(s_f, \bar{s}, z_i) = & (1 - \alpha)e^\zeta f(\hat{k}h)z_i l_i - \hat{w}_i + (1 - \alpha)e^\zeta f(\hat{k}h)N \int_{\tilde{z}}^{\infty} z \frac{\partial l(\cdot, z)}{\partial N} d\tilde{\Omega}(z) \\ & - N \int_{\tilde{z}}^{\infty} \frac{\partial \hat{w}(\cdot, z)}{\partial N} d\tilde{\Omega}(z) + (1 - \bar{\rho})Q(\bar{s})e^{\gamma_y} E [\Pi_M(s'_f, \bar{s}') | \bar{s}]. \end{aligned} \quad (31)$$

This expression deserves some discussion. The first term on the right hand side of the equation is worker i 's marginal productivity. The second term subtracts worker i 's wage. Moreover, the firm takes into account the effect upon the wage and hours bargained with the other workers of adding (or keeping) worker i . Those effects are represented by the third and fourth terms. The last term denotes the discounted expected value of the worker in the future, which is given by next-period marginal value of a match $\Pi_M(s', \bar{s}')$. Notice then that the following condition holds

$$\begin{aligned} \Pi_M(s, \bar{s}) &= (1 - \Omega(\tilde{z})) \int_{\tilde{z}}^{\infty} \mathcal{W}^J(s_f, \bar{s}, z) d\tilde{\Omega}(z) \\ &= \int_{\tilde{z}}^{\infty} \mathcal{W}^J(s_f, \bar{s}, z) d\Omega(z). \end{aligned} \quad (32)$$

This simply says that the value of a match (before z is drawn) has to be equal to

¹⁵This intrafirm bargaining have been used by others such as Cahuc and Wasmer (2001) and Ebell and Haefke (2006). The latter argue that not only individual bargaining is the natural extension of the standard Mortensen-Pissarides matching model to an environment with multi-worker firms, but also it better characterizes the U.S. labor market.

the expected value of a job (employed worker) weighted by $(1 - \Omega(\tilde{z}))$. Notice that $\Omega(\tilde{z})M$ workers have zero value for the firm. It is straightforward to check that (31) satisfies this condition.

The (net) value of being employed is described by the following equation

$$\begin{aligned} \mathcal{W}^E(s_h, \bar{s}, z_i) = \hat{w}_i + \frac{\hat{c}^{\psi(1-\sigma)}[(1 - l_i)^{(1-\psi)(1-\sigma)} - 1]}{(1 - \sigma)\lambda} - \frac{e^{\gamma_y} b}{\lambda} \\ + [(1 - \bar{\rho}) - \theta q(\theta)]Q(\bar{s})e^{\gamma_y} E \left[\frac{\mathcal{V}_m(s'_h, \bar{s}')}{\lambda'} \middle| \bar{s} \right], \end{aligned} \quad (33)$$

where λ is equal to the marginal utility of consumption as shown above, and $\mathcal{V}_M$ denotes the household's marginal value of having a worker matched with a firm next period.

Similarly to the value of a job, it follows that

$$\begin{aligned} \frac{\mathcal{V}_m(s_h, \bar{s})}{\lambda} &= (1 - \Omega(\tilde{z})) \int_{\tilde{z}}^{\infty} \mathcal{W}^E(s_h, \bar{s}, z) d\tilde{\Omega}(z) \\ &= \int_{\tilde{z}}^{\infty} \mathcal{W}^E(s_h, \bar{s}, z) d\Omega(z). \end{aligned} \quad (34)$$

The Nash bargaining solution is a wage rate w_i and hours l_i that solve

$$\max_{w_i, l_i \in [0,1]} \mathcal{W}^E(s_h, \bar{s}, z_i)^\eta \mathcal{W}^J(s_f, \bar{s}, z_i)^{1-\eta}, \quad (35)$$

with η represents the worker's bargaining power. This yields the following wage schedule and hours:

$$\begin{aligned} \hat{w}(\cdot, z_i) = (1 - \eta) \left\{ \frac{\hat{c}^{\psi(1-\sigma)}[1 - (1 - l(\cdot, z_i))^{(1-\psi)(1-\sigma)}]}{(1 - \sigma)\lambda} + \frac{e^{\gamma_y} b}{\lambda} \right\} \\ + \eta \left\{ (1 - \alpha)e^\zeta f(\hat{k}h) \left[z_i l(\cdot, z_i) + N \int_{\tilde{z}}^{\infty} z \frac{\partial l(\cdot, z)}{\partial N} d\tilde{\Omega}(z) \right] \right. \\ \left. - N \int_{\tilde{z}}^{\infty} \frac{\partial \hat{w}(\cdot, z)}{\partial N} d\tilde{\Omega}(z) + e^{\gamma_y} \kappa \theta \right\}, \end{aligned} \quad (36)$$

$$l(\cdot, z_i) = 1 - \left[\frac{\lambda}{(1 - \psi)\hat{c}^{\psi(1-\sigma)}} (1 - \alpha) e^\zeta f(\hat{k}h) z_i \right]^{\frac{1}{\psi\sigma - \psi - \sigma}}. \quad (37)$$

It is important to point out that for the resulting hours (37), the marginal product of labor equals the marginal rate of substitution between consumption and leisure. In other words, in the bargaining process, the firm and workers seek to maximize the total surplus of each match when choosing hours. Wages are then determined according to the Nash rule.

The differential equation for the wage (36) can be simplified as follows. First notice that hours worked do not depend on N because, as we showed above, $\hat{k}$ and h do not depend on the firm's employment level, and λ and $\hat{c}$ do not either. Thus,

$$N \int z \frac{\partial l(\cdot, z)}{\partial N} d\tilde{\Omega}(z) = 0.$$

Now we rewrite (36) as

$$\hat{w}(\cdot, z_i) = \Psi(z_i, \bar{s}) - \eta N \int_{\bar{z}}^{\infty} \frac{\partial \hat{w}(\cdot, z)}{\partial N} d\tilde{\Omega}(z),$$

where

$$\begin{aligned} \Psi(z_i, \bar{s}) = (1 - \eta) \left\{ \frac{\hat{c}^{\psi(1-\sigma)} [1 - (1 - l(\cdot, z_i))^{(1-\psi)(1-\sigma)}]}{(1 - \sigma)\lambda} + \frac{e^{\gamma y} b}{\lambda} \right\} \\ + \eta \left\{ (1 - \alpha) e^\zeta f(\hat{k}h) z_i l(\cdot, z_i) + e^{\gamma y} \kappa \theta \right\}. \end{aligned}$$

Notice that $\Psi(z_i, \bar{s})$ does not depend on N . Therefore, the wage does not depend on N either, and

$$N \int \frac{\partial \hat{w}(\cdot, z)}{\partial N} d\tilde{\Omega}(z) = 0.$$

Accordingly, the wage function simplifies as

$$\hat{w}(s, \bar{s}, z_i) = (1 - \eta) \left\{ \frac{\hat{c}^{\psi(1-\sigma)} [1 - (1 - l(s, \bar{s}, z_i))^{(1-\psi)(1-\sigma)}]}{(1 - \sigma)\lambda} + \frac{e^{\gamma_y} b}{\lambda} \right\} + \eta \left\{ (1 - \alpha) e^\zeta f(\hat{k}h) z_i l(s, \bar{s}, z_i) + e^{\gamma_y} \kappa \theta \right\}, \quad (38)$$

with $s = (s_f, s_h)$.

3.4 Equilibrium

Definition 1 *A recursive equilibrium in this stationary economy is a set of functions for:*

- *Prices:* $Q(\bar{s})$, $\hat{w}(s, \bar{s}, z)$, $r(\bar{s})$;
- *Quantities:* $g_K(s, \bar{s})$, $g_z(s, \bar{s})$, $g_h(s, \bar{s})$, $g_v(s, \bar{s})$, $g_c(a, \bar{s})$, $g_a(a, \bar{s})$, $l(s, \bar{s}, z)$, $G_A(\bar{s})$, $G_K(\bar{s})$, $G_M(\bar{s})$, $\Theta(\bar{s})$, $\tilde{Z}(\bar{s})$;
- *Values:* $\Pi(s_f, \bar{s})$, $\mathcal{V}(s_h, \bar{s})$, $\mathcal{W}^J(s_f, \bar{s}, z)$, $\mathcal{W}^E(s_h, \bar{s}, z)$;

such that:

- i. $\mathcal{V}(s_h, \bar{s})$ solve the representative consumer's problem (26) with associated policy functions $g_c(s_h, \bar{s})$, $g_a(s_h, \bar{s})$;
- ii. $\Pi(s_f, \bar{s})$ solves the firm's problem (18) with associated policy functions $g_K(s_f, \bar{s})$, $g_M(s_f, \bar{s})$, $g_z(s_f, \bar{s})$, $g_h(s_f, \bar{s})$, $g_v(s_f, \bar{s})$;
- iii. the wage schedule $\hat{w}(s, \bar{s}, z)$ and hours $l(s, \bar{s}, z)$ solve the individual Nash bargaining problem (35) for $z \geq \tilde{z}$;
- iv. the interest rate $r(\bar{s})$ clears the capital market;
- v. $Q(\bar{s})$ clears the asset market; and

vi. the following consistency conditions hold:

$$\begin{aligned}
G_A(\bar{s}) &= I \times g_a(\bar{s}, \bar{s}), \\
G_K(\bar{s}) &= g_K(\bar{s}, \bar{s}), \\
G_M(\bar{s}) &= \bar{M}(1 - \Omega(g_z(\bar{s}, \bar{s}))(1 - \bar{\rho}) + q(\theta)g_v(\bar{s}, \bar{s}), \\
\Theta(\bar{s}) &= g_v(\bar{s}, \bar{s})/\{1 - \bar{M}[1 - \Omega(g_z(\bar{s}, \bar{s}))]\}, \\
\tilde{Z}(\bar{s}) &= g_z(\bar{s}, \bar{s}), \\
\Pi(G_s(\bar{s}), G_s(\bar{s})) &= I \times g_a(\Pi(\bar{s}, \bar{s}), \bar{s}).
\end{aligned}$$

4 Calibration

In this section we calibrate the model at quarterly frequency to be consistent with some empirical facts for the postwar (WWII) U.S. economy. In particular, the parametrization must match eight steady-state targets. From the RBC literature we take three standard statistics. A capital's share of output of about one third, consistent with the NIPA; a quarterly interest rate of about 1 percent; and a depreciation rate of 2.5 percent per quarter. We also target an average annual growth rate of GDP per capita of 1.91 percent. It corresponds to the annual average growth rate of the Real Gross Domestic Product divided by civilian noninstitutional population. The GDP is taken from the NIPA while civilian population is taken from the BLS.

The remaining four targets are related to labor market outcomes. First, we set an average unemployment rate u^* of 11 percent. This figure is consistent with the fraction of unmatched workers in the U.S. when we consider not only the officially unemployed but also those not in the labor force who “want a job”. Using the CPS from 1968 to 1986, Blanchard and Diamond (1990) find that on average there are 11.2 million people either unemployed (6.5) or not in the labor force who want a job

(4.7) out of a total of 104.4 million workers (93.2 millions employed).¹⁶

Secondly, we target a steady-state job separation probability ρ^* equal to 0.10 per quarter.¹⁷ This value is commonly used in the literature (see Shimer, 2005; den Haan, Ramey, and Watson, 2000, among others), and is consistent with available empirical estimates. Hall (1995) concludes that the average quarterly separation rate in the U.S. is between 8 and 10 percent. Moreover, Davis, Haltiwanger, and Schuh (1996) use CPS data and find an annual separation rate of 36.8 percent, which is roughly equivalent to our quarterly target.

We also target an elasticity of the matching function with respect to unemployment ε_μ^* of 0.50 as in Pissarides (2009). This value is consistent with empirical evidence reported by Petrongolo and Pissarides (2001), who argue in their survey paper that a “plausible range for the empirical elasticity on unemployment is 0.5 to 0.7” (p. 393). For comparative purposes, in an alternative parametrization we target a matching elasticity of 0.72. Shimer (2005) finds this elasticity when estimating the parameters of a Cobb-Douglas matching function for the U.S. using data on the job finding rate and the vacancy-unemployment ratio. As in Bils, Chang, and Kim (2009), our final target is a Frisch labor supply elasticity of one third. As pointed out by these authors, much of the evidence suggests a value of 0.5 or below.

We need to find values the following parameters: β, σ, ψ, b (preferences), α (technology), ω, ξ (depreciation), φ (matching function), $\bar{\rho}$ (exogenous job separation), κ (vacancy cost), η (workers bargaining power). We also must select values for the long-run growth rates γ_y^* and γ_v^* as well as for parameters $\rho_\zeta, \sigma_\zeta, \rho_v$, and σ_v , which govern the stochastic processes for random variables ζ and γ_v . Finally, we need to set the standard deviation of $\log z, \sigma_z$.

¹⁶Other studies on labor market dynamics also use Blanchard and Diamond’s (1990) figures to calibrate their models. For instance, den Haan, Ramey, and Watson (2000) target a steady-state ratio of unmatched to matched workers of 0.12. In Yashiv (2006), the average unemployment rate is set at 10.4. His computed unemployment rate is extremely correlated with the official rate (0.98).

¹⁷Starred variables denote their steady-state levels.

The elasticity of output with respect to capital α is set equal to $1/3$, coinciding with the average capital's share of output mentioned above. It is important to notice that in this setting, where wages are not equal to the marginal productivity of labor, $(1 - \alpha)$ does not necessarily coincide with the labor's share of output.

The coefficient of relative risk aversion σ is chosen to be 2. We also set $\psi = 0.727$ to match our target of $1/3$ for the Frisch labor supply elasticity.

Using equations (19), (21) and (23), we obtain the following condition for steady-state capital utilization h^* ,

$$h^* = \left(\frac{\omega(1 - Q^*)}{\xi Q^*(\omega - 1)} \right)^{1/\omega}.$$

Notice that h^* and, consequently, $\delta(h^*)$ only depend on ω and ξ for given $Q^* = \beta e^{\gamma_y^*(\psi(1-\sigma)-1)}$. We normalize $h^* = 1$, and choose $\omega = 1.847$ and $\xi = 0.046$ such that $\delta(h^*) = 0.025$, consistent with our target for the average depreciation rate.

The parameters for the stochastic process for the aggregate shock ζ are taken from Hansen and Wright (1992). We set $\rho_\zeta = 0.95$ and $\sigma_\zeta = 0.007$. The long-run growth of output γ_y^* is set to 0.0047 to match the average annual growth rate of GDP per capita. The parameters γ_v^* , ρ_v and σ_v are set to match the stochastic properties of the growth rate of relative price of new equipments used in Section 2. When we estimate the first-order autoregressive equation (2), we obtain $\gamma_v^* = 0.011$, $\rho_v = 0.700$ and $\sigma_v = 0.0059$.¹⁸

It is somewhat common in the literature to obtain the stochastic properties of the relative price of investment by estimating a least squares regression of in log-levels with a linear time trend and an AR(1) error term.¹⁹ Instead, we have estimated a first-order autoregressive process of the first log difference of the (inverse of) relative

¹⁸In particular, we estimate the following equation:
 $\gamma_{v,t} = 0.0033 + 0.700\gamma_{v,t-1} + \nu_{v,t}$ with $\sigma_{\nu_v} = 0.0059$; $R^2 = 0.491$; and coefficient standard errors 0.0011 and 0.077, respectively.

¹⁹See, for example, Greenwood, Hercowitz, and Krusell (2000) and De Bock (2007).

price of investment. Notice that our estimate of the persistence parameter $\rho_v = 0.70$ for the growth rate of relative price of new equipments implies that the log-level of the relative price of investment does not follow a stationary AR(1) process around a time trend. If this were the case, ρ_v must be between -1/2 and 0.²⁰

The standard deviation of random variable $\log(z)$ is set to $\sigma_z = 0.2$. According to Zanetti (2007), the literature provides a range of values between 0.1 and 0.4 for the standard deviation of the distribution of the idiosyncratic shocks, and we choose an intermediate value. Regarding the exogenous separation probability $\bar{\rho}$, we choose two values. For our baseline value, following den Haan, Ramey, and Watson (2000), we interpret exogenous separations as worker-initiated separations. Hence, endogenous separations are associated with the layoff rate. This is consistent with our model since endogenous separations are a firm's decision. According to the evidence from JOLTS shown by Davis, Faberman, and Haltiwanger (2006) and from the Census' Survey of Income and Program Participation (SIPP) shown by Nagypal (2004), layoffs represent on average about 35 percent of total separations. Thus, one of the values we pick for $\bar{\rho}$ is 0.065, which is close to the one used by den Haan, Ramey, and Watson (2000). They set this parameter to 0.068 using a slightly different calibration strategy. We consider this exogenous probability as an upper bound because most of the quits are in fact job-related quits, which can hardly be classified as exogenous (see Nagypal, 2004, for details). Therefore, we also consider $\bar{\rho} = 0.035$.

We select the matching technology parameter φ in order to match our target for $\mathcal{E}_\mu^*$. Since the matching elasticity depends on θ as well, we need to solve the following

²⁰If, as in Greenwood, Hercowitz, and Krusell (2000), the inverse of the relative price of investment Υ_t follows a process of the form $\ln \Upsilon_t = \text{constant} + t \ln \gamma + \eta_t$, where $\eta_t = \rho \eta_{t-1} + \epsilon_t$ with $0 < \rho < 1$ and $\epsilon_t \sim N(0, \sigma)$, then the persistent coefficient of the growth rate of Υ (i.e., our parameter ρ_v) is equal to $(2\rho - \rho^2 - 1)/(2(1 - \rho))$. As a result, the values of ρ_v must be between -1/2 and 0.

system of equation for φ and θ^* ,

$$\begin{aligned}\frac{\theta^{*\varphi}}{(1 + \theta^{*\varphi})} &= \mathcal{E}_\mu^*, \\ \rho^*(1 - u^*) &= (1 - \Omega(\tilde{z}^*))q(\theta^*; \varphi)\theta^*u^*.\end{aligned}$$

The first equation is the elasticity of the matching function with respect to unemployment in the steady state. The second expression comes from the law of motion for employment given by equations (6) and (10). The left-hand side of represents employment-to-unemployment transitions whereas the right-hand side determines unemployment-to-employment transitions. Clearly, in the steady state they must be equal so that the unemployment rate remains constant. Notice that the steady-state job finding probability $j(\theta^*, \tilde{z}^*) = (1 - \Omega(\tilde{z}^*))\theta^*q(\theta^*)$ must be equal to $\rho^*(1 - u^*)/u^* = 0.81$. For our baseline parametrization (i.e., $\bar{\rho} = 0.065$ and $\mathcal{E}_\mu^* = 0.50$), we obtain $\varphi = 3.991$. Table 5 displays the values for alternative calibrations.

According to the Hosios (1990) condition for efficiency, we internalize the search externality in the model by setting the bargaining power parameter η equal to our target elasticity of the matching function with respect to unemployment, $\eta = \mathcal{E}_\mu^*$. It is somewhat common in the recent literature to calibrate the matching model by assuming the condition for efficiency (see, for example, Pissarides, 2009; Shimer, 2005). However, there seems not to be a consensus on this value. Most of this literature chooses it in a somewhat arbitrary way.

Parameters κ and b are chosen so that the first-order conditions (20) and (22) are satisfied in the steady state. Thus, we set $\kappa = 0.173$ and $b = 0.404$. To put the value of κ in perspective, we calculate the total vacancy cost $e^{\gamma_y^*}\kappa v^*$ in the steady state, and find that it represents about 1 percent percent of total output.

As for our calibrated value of b , which includes home production, leisure activities and unemployment benefits, it implies that the opportunity cost of employment

represents about 45 percent of the average wage, and nearly 30 percent of output per worker in the steady state.

Finally, we pin down the subjective discount factor β by using the fact that the (gross) interest rate R must satisfy the following equilibrium condition in the steady state

$$1/R^* = \beta e^{\gamma_y^*(\psi(1-\sigma)-1)}.$$

This expression comes from condition (30) given that $Q = 1/R$ in equilibrium. Given all the relevant parameters and our target for the average quarterly interest rate of 1 percent, we set $\beta = 0.998$.

Table 4: COMMON PARAMETER VALUES

Parameter	Calibrated value	Parameter	Calibrated value
σ	2	ρ_ζ	0.95
β	0.998	σ_ζ	0.007
α	0.333	ρ_v	0.70
ω	1.847	σ_v	0.0059
ξ	0.046	γ_y^*	0.0047
η	0.50	γ_v^*	0.011
σ_z	0.20		

Table 5: REMAINING PARAMETER VALUES

	Baseline	Parameterization B	Parameterization C
ε_μ^*	0.50	0.50	0.72
$\bar{\rho}$	0.065	0.035	0.065
ψ	0.727	0.731	0.727
b	0.404	0.416	0.404
φ	3.991	4.878	1.891
κ	0.173	0.161	0.105

4.1 Simulation results

In this subsection we assess the quantitative importance of investment-specific shocks for cyclical fluctuations in the labor market. We do so by simulating our calibrated

economy with and without this type of shocks. That is, in the former case σ_v takes its baseline value shown in Table 4, whereas in the latter we set $\sigma_v = 0$. Note that the remaining parameter values remain the same. We then compare the relevant statistics for the two simulated economies.

More in detail, we perform Monte Carlo simulations with 5000 realizations. In order to perform the simulations, we first solve the stationarized version of model by using a first order log-linearization procedure which we implement in Dynare for Matlab.²¹ In each iteration, we let the economy run for 1184 periods and only take the simulated data of the last 184 periods (the same number of quarters for the data on the relative price of investment p_e). We then add back the corresponding nonstationary component to our simulated data, which is also logged and HP-filtered (with smoothing parameter equal to 1600) in the same way as we do with the U.S. data before calculating the statistics of interest. Finally, we compute the average of these simulated statistics over the 5000 realizations. Tables 6 and 7 show the results.

The main result is that investment-specific shocks play a role in amplifying labor market fluctuations. This can be seen by comparing columns 2 and 5 in the upper panel of Table 6. When investment shocks are operative (column 2), the standard deviation of vacancies is 4.8 times larger (5.77 vs. 1.20) whereas unemployment volatility is about 3 times higher (8.74 vs. 2.89). Most of the increase in the latter is explained by a 4.3 times increment in the standard deviation of the job destruction probability (7.85 vs. 1.84). The volatility of the job finding probability is also larger but in a more modest magnitude (2.82 vs. 1.86). This implies that the job destruction margin is much more sensitive to shocks to the relative price of investment.

Moreover, the standard deviations of employment and hours worked are also 3 and 1.7 times larger, respectively, when Υ -shocks are operative. This indicates that the extensive margin is relatively more sensitive to this type of shocks.

²¹The Dynare code and related programs can be downloaded at Manuel Toledo's webpage <http://sites.google.com/site/metoledo/home>.

Table 6: SIMULATION RESULTS: STANDARD DEVIATIONS

	U.S. Data (1)	Benchmark Model			No Inv. Shocks (5)	No Cap. Utilizat. (6)	No Endog. Separation (7)
	(1)	Baseline (2)	B (3)	C (4)	(5)	(6)	(7)
<i>Standard deviations (%):</i>							
Output	1.56	1.78	2.01	1.80	1.48	1.25	1.44
Investment	5.18	5.68	6.66	5.78	3.76	3.78	4.18
Consumption	1.11	0.80	0.75	0.78	0.54	0.59	0.81
Cap. Utilization	2.41	1.58	1.65	1.58	0.77	-	1.44
Total hours	1.87	1.45	2.00	1.54	0.58	1.02	0.45
Hours per worker	0.44	0.39	0.44	0.41	0.23	0.26	0.33
Employment	0.98	1.08	1.62	1.14	0.36	0.79	0.15
Unemployment	11.03	8.74	13.1	9.26	2.89	6.40	1.23
Vacancies	13.34	5.77	9.73	6.44	1.20	4.83	2.11
Job finding rate	7.36	2.82	3.25	1.89	1.86	1.77	1.42
Separation rate	4.63	7.85	12.51	9.04	1.84	5.98	-
Labor productivity	1.35	1.18	1.17	1.13	1.15	1.01	1.33
Wages	0.89	1.23	1.24	1.21	1.13	1.01	1.29
<i>Relative standard deviations with respect to output:</i>							
Investment	3.32	3.19	3.31	3.21	2.54	3.04	2.90
Consumption	0.71	0.45	0.37	0.43	0.36	0.47	0.56
Cap. Utilization	1.54	0.89	0.82	0.88	0.52	-	1.00
Total hours	1.20	0.81	1.00	0.86	0.39	0.82	0.31
Hours per worker	0.28	0.22	0.23	0.14	0.16	0.23	0.14
Employment	0.63	0.61	0.61	0.63	0.24	0.63	0.10
Unemployment	7.07	4.91	6.52	5.14	1.95	5.12	0.85
Vacancies	8.55	3.24	4.84	3.58	0.81	3.86	1.47
Job finding rate	4.72	1.58	1.62	1.05	1.26	1.42	0.99
Job separation rate	2.97	4.41	6.22	5.02	1.24	4.78	-
Labor productivity	0.87	0.66	0.58	0.63	0.78	0.81	0.92
Wages	0.57	0.69	0.62	0.67	0.76	0.81	0.90

Investment-specific shocks also play a role in amplifying the labor market volatility relative to fluctuations in output. The lower panel of Table 6 displays standard deviations relative to the standard deviation of output. With investment specific shocks, unemployment and vacancies are 4.9 and 3.2 times more volatile than output (column 2), respectively. However, when we eliminate this source of shocks the relative volatility of unemployment is reduced to 1.95 and vacancies become less volatile than

Table 7: SIMULATION RESULTS: PERSISTENCE AND CORRELATIONS

	U.S. Data (1)	Benchmark Model			No Inv. Shocks (5)	No Cap. Utilizat. (6)	No Endog. Separation (7)
		Baseline (2)	B (3)	C (4)			
<i>Correlation with output:</i>							
Investment	0.84	0.94	0.96	0.95	0.99	0.94	0.92
Consumption	0.77	0.37	0.35	0.40	0.98	0.53	0.48
Cap. Utilization	0.56	0.69	0.68	0.69	0.96	-	0.70
Total hours	0.89	0.80	0.84	0.83	0.98	0.68	0.86
Hours per worker	0.71	0.89	0.92	0.90	0.99	0.88	0.81
Employment	0.79	0.75	0.81	0.79	0.95	0.59	0.76
Unemployment	-0.85	-0.75	-0.81	-0.79	-0.59	-0.76	-0.90
Vacancies	0.90	-0.37	-0.62	-0.53	0.60	-0.26	0.88
Job finding rate	0.82	0.81	0.85	0.84	0.79	0.72	0.76
Job separation rate	-0.56	-0.68	-0.77	-0.76	-0.51	-0.50	-
Labor productivity	0.68	0.80	0.59	0.78	0.99	0.77	0.99
Wages	0.22	0.67	0.48	0.64	0.99	0.66	0.95
<i>Autocorrelation:</i>							
Output	0.84	0.73	0.70	0.71	0.72	0.68	0.74
Investment	0.85	0.67	0.64	0.65	0.72	0.63	0.70
Consumption	0.81	0.59	0.62	0.60	0.73	0.66	0.57
Cap. Utilization	0.48	0.90	0.90	0.90	0.80	-	0.89
Total hours	0.91	0.68	0.64	0.66	0.79	0.69	0.76
Hours per worker	0.72	0.55	0.51	0.56	0.63	0.50	0.61
Employment	0.87	0.72	0.67	0.70	0.84	0.74	0.77
Unemployment	0.88	0.72	0.67	0.70	0.83	0.74	0.77
Vacancies	0.90	0.67	0.52	0.66	0.03	0.70	0.42
Job finding rate	0.80	0.78	0.79	0.80	0.74	0.80	0.73
Job separation rate	0.46	0.58	0.55	0.60	0.61	0.63	-
Labor productivity	0.77	0.66	0.65	0.66	0.66	0.69	0.69
Wages	0.80	0.66	0.65	0.65	0.67	0.68	0.69

output (0.81 in column 5).

Comparing to the data, the baseline model generates 80, 90 and 110 percent of the observed standard deviations in unemployment, hours worked and employment, respectively. Despite this improvement, the model shows relatively low variability in vacancies and job finding probability, with standard deviations that are at most 40 percent as volatile as in the data. In contrast, job separation and wages are much

more volatile than in the data.

Relative to output, volatilities are, in general, smaller to the ones observed in the data. For instance, while vacancies and unemployment fluctuate 3.2 and 4.9 times more than output in our model, in the U.S. labor market these numbers are 8.55 and 7.07, respectively. One important exception is the job separation probability, with a simulated relative standard deviation of 4.41, which is higher than the value of 2.97 observed in the data. Wages also display a larger relative volatility.

Investment-specific shocks also amplify the volatility of the remaining variables. As expected, the standard deviation of output falls by 17 percent (from 1.78 to 1.48) when we shut them down. Furthermore, the standard deviations of investment and capital utilization fall significantly from 5.68 and 1.58 to 3.76 and 0.77, respectively. This is expected since this type of shocks directly affects the optimal conditions (19) and (21) governing these two decisions.

Thus, the mechanism behind the positive impact of investment shocks on labor market fluctuations can be described as follows. A positive shock reduces the user cost of capital, which stimulates investment and capital utilization. As a result, the effective capital per worker kh increases, which implies a higher marginal product of labor. Thus, firms find optimal to increase hours worked and employment. The latter is achieved by posting more vacancies and avoiding job destruction.

Consumption also becomes less volatile when the investment-specific shock is not operative. The fall of the standard deviation of both consumption and investment are tightly related. In fact, the intuition is fundamentally the same. A fall in the relative price of investment goods (i.e., a positive shock) makes agents substitute investment away from consumption. Thus, removing this direct source of investment volatility leads to a significant drop in consumption fluctuations. As shown in the upper panel of Table 7, this substitution effect also explains the decrease in the correlation between consumption and output from 0.98 to 0.37 when there are investment-specific shocks.

The relevance of capital utilization as transmission channel of shocks can be measured by shutting down this margin (columns 6 in Table 6). As observed in upper panel of the table, the standard deviations of all of the variables fall compared with our baseline economy (column 2). In particular, the standard deviation of unemployment and vacancies decrease from 8.74 and 5.77 in the baseline model to 6.40 and 4.83 in the model without capital utilization, respectively. Hence, as expected, variable capital utilization provides the model an amplification mechanism to shocks. However, when we look at the relative volatilities in the lower panel of the table, the amplification effect of capital utilization goes, in general, in the opposite direction. This indicates that capital utilization has a stronger amplification over output than over the other variables, especially labor market variables. This is a somewhat intuitive result because the capital utilization margin works as a substitute for both hours and employment (i.e., labor services in general).

Now the question is how important endogenous capital utilization is in amplifying investment-specific shocks in particular. To that end, we simulate the model with no capital utilization margin and see how much larger the volatilities are when investment shocks are operative, relative to the case when these shocks are shut down.²² We observe that the volatility of output, investment and consumption only increase 12, 42 and 20 percent, respectively. Instead, in the model with variable capital utilization, these volatilities are 20, 51 and 48 percent larger when there are investment shocks. Thus, clearly endogenous capital utilization help amplify this type of shocks as far as output, investment and consumption go.

However, when it comes to labor market fluctuations, variable capital utilization dampens the amplification effect of investment-specific shocks. For instance, in the model with no capital utilization margin, the standard deviation of unemployment is almost 4 times bigger when investment shocks are operative. In our baseline model,

²²We do not show the result of this simulation in our tables.

it is around 3 times larger. In the case of vacancies, fluctuations are 5.4 versus 4.8 times larger. Total hours are also more responsive to investment-specific shocks when there is no variable capital utilization (2.83 vs. 2.5). The same can be said about output per worker and wages although the difference is smaller. The only exception is hours per worker. Its standard deviation increases 63 percent when Υ -shocks become operative in the model with no capital utilization. This increment is smaller than the 70 percent increase in our baseline economy.

The intuition of this opposite amplification effect of endogenous capital utilization on the volatility of output as well as investment and consumption, on the one hand, and on labor market variables, on the other hand, is the same as before. That is, capital utilization serves as a substitute for labor services, which therefore do not respond as much to investment shocks.

Our model is similar to that presented in Faccini and Ortigueira (2009). However, these authors do not include endogenous capital utilization and only consider exogenous adjustment in the job separation rate. In contrast, our model does not introduce convex adjustment costs in capital and labor as theirs do. Contrary to our result, in their benchmark simulation with the same two types of technological shocks, vacancies are relatively more volatile than unemployment. Their model is able to reproduce 22 and 40 percent of the observed standard deviations in unemployment and vacancies, respectively (see their table 6). Our baseline model is able to reproduce 79 and 40 percent instead. Thus, while having capital utilization and endogenous job destruction help raise the volatility of unemployment, it seems that the existence of convex adjustment costs in capital and labor increase the volatility of vacancies relative to unemployment.

Results from our baseline calibrated model reveal one important counterfactual predictions regarding the labor market. That is, the contemporaneous correlation of vacancies with output is negative in the model (-0.37), whereas the empirical evidence

says that it is strongly procyclical for the U.S. economy. As a consequence, we obtain a significant positive correlation of 0.88 between vacancies and unemployment in contrast to the observed coefficient of -0.92 in the data. Thus, the baseline model is unable to reproduce the so-called Beveridge curve.

The baseline model predicts this counterfactual correlation of vacancies and unemployment mainly due to the large fraction of endogenous job destruction. As pointed out by Krause and Lubik (2007), when the exogenous separation probability increases and gets closer to the steady-state separation rate, the model delivers a lower correlation between vacancies and unemployment. Indeed, when we make $\bar{\rho} = .10$ and, consequently, there are no endogenous job destruction in the steady state, we obtain a correlation of -0.40 .²³ We also observe a switch of sign in the correlation between vacancies and output from -0.37 to 0.88 (see column 7 in Table 7). Thus, vacancies are now strongly procyclical. Another example comes from our parameterization B (column 3). With a lower $\bar{\rho} = .035$, the model produces a even more countercyclical behavior of vacancies and, in consequence, a more positive vacancies-unemployment correlation. Also notice that endogenous job destruction significantly amplifies the labor market fluctuations. For example, when exogenous job separations accounts for 35% of total separations, the volatility of vacancies and unemployment jump from 8.74 and 5.77 in the baseline simulation to 13.1, and 9.73, respectively.

As we mention before, the unemployment-elasticity of the matching function used in the literature varies considerably (see Hagedorn and Manovskii, 2008, for a discussion). Different values for the matching elasticity affects the quantitative results in different directions. For example, when we increase ε_{μ}^* from 0.5 in our baseline parameterization to 0.72 in parameterization C, the standard deviation of job separations and unemployment are increased, while standard deviations of job finding is

²³Here we recalibrate the model so that the steady-state job creation optimality condition is satisfied and the targets remain unchanged. Also notice that out of the steady state, there might be endogenous job destruction.

reduced (see column 4 of the first block in Table 6).

Finally, the second block of Table 7 shows lower persistence in most of the simulated series in the benchmark model (column 2) with respect to the data (column 1) . This is particularly significant in the case of vacancies, with a autocorrelation coefficient of 0.67 in the baseline model with respect to 0.90 in the U.S. data.

5 Conclusions

In this paper we provide evidence from the postwar period in the U.S. that shows a link between relative prices and labor market variables. This evidence suggests that when technological advances make equipment less expensive, the investment in new equipment increases together with the vacancies, employment and hours worked, at least in the short run.

We present a quantitative model that can account for this empirical facts as well as other standard business cycle facts. The model is able to generate an extra amplification mechanism in the labor market. Thus, the volatility of relevant labor market variables increase when investment shocks are incorporated into the model. Moreover, the relatively smaller increase in the simulated standard deviation in hours per worker with respect to employment implies that extensive margin is relatively more sensitive to investment-specific shocks. Comparing to the data, the baseline model generates 80, 90 and 110 percent of the observed standard deviations in unemployment, hours worked and employment, respectively. However, it still shows relatively low variability in vacancies and job finding probability with standard deviations that are at most 40 percent as volatile as in the data.

Another important result is that having endogenous separations in the model seems to introduce a meaningful amplifying effect. However, with a reasonable fraction of endogenous job destruction, the model delivers important counterfactual pre-

dictions with respect to the behavior of vacancies and unemployment. It is true that more endogenous separations amplify the fluctuations of both vacancies and, especially, in unemployment. However, this leads the model to fail to reproduce the observed negative relationship between vacancies and unemployment (the downward-sloping Beveridge curve). Our simulated results also show that capital utilization has a stronger amplification mechanism over output than over the other variables, especially labor market variables. This result takes place because the capital utilization margin works as a substitute for labor services.

A Appendix

A.1 System of equilibrium equations

Here we describe the full set of equations characterizing the equilibrium in the model economy described in Section 3. This system of nonlinear differential equations is the one implemented in Dynare, which solves a first-order log-linearized version of it. The system of equations consists of first order conditions from both the firm's and consumer's problem, laws of motion for the state variables, resource constraints, and other auxiliary variable definitions. From these equations we also characterize the non-stochastic steady state relations. Note that notation in this Appendix might be slightly different from the text above.

From the firm's problem we get the following optimality conditions:

$$\frac{1}{Q_t} = E \left[e^{\zeta_{t+1}} \alpha h_{t+1} k_{ht+1}^{\alpha-1} + \frac{1 - \delta_{t+1}}{e^{\gamma_{vt+1}}} \right], \quad (\text{A1})$$

$$\frac{\kappa}{q_t Q_t} = E \left\{ (1 - \tilde{\Omega}_{t+1}) \left[e^{\zeta_{t+1}} (1 - \alpha) k_{ht+1}^\alpha \bar{l}_{zt+1} - \bar{w}_{t+1} + e^{\gamma_{yt+1}} (1 - \bar{\rho}) \frac{\kappa}{q_{t+1}} \right] \right\}, \quad (\text{A2})$$

$$\xi h_t^{\omega-1} = e^{\zeta_t + \gamma_{vt}} \alpha k_{ht}^{\alpha-1}, \quad (\text{A3})$$

$$\tilde{w}_t = (1 - \alpha) e^{\zeta_t} k_{ht}^\alpha \tilde{z}_t \bar{l}_t + e^{\gamma_{yt}} (1 - \bar{\rho}) \frac{\kappa}{q_t}, \quad (\text{A4})$$

with

$$\delta_t = \xi h_t^\omega / \omega, \quad (\text{A5})$$

$$k_{ht} = k_t h_t, \quad (\text{A6})$$

$$k_t = K_t / L_t, \quad (\text{A7})$$

$$L_t = N_t \bar{l}_{zt}, \quad (\text{A8})$$

$$\bar{l}_{zt} = \bar{z}_t - \hat{z}_t \left[\frac{\lambda_t}{(1 - \psi) C_t^{\psi(1-\sigma)}} (1 - \alpha) e^{\zeta_t} k_{ht}^\alpha \right]^{\frac{1}{\psi\sigma - \psi - \sigma}}, \quad (\text{A9})$$

$$\bar{z}_t = \exp(\sigma_z^2/2) \left[\frac{\Phi(\sigma_z - \log(\tilde{z}_t)/\sigma_z)}{\Phi(-\log(\tilde{z}_t)/\sigma_z)} \right], \quad (\text{A10})$$

$$\hat{z}_t = \exp \left[\underbrace{\left(\frac{(1-\psi)(1-\sigma)\sigma_z}{\psi\sigma - \psi - \sigma} \right)^2}_{\hat{\sigma}_z} / 2 \right] \left[\frac{\Phi(\hat{\sigma}_z - \log(\tilde{z}_t)/\hat{\sigma}_z)}{\Phi(-\log(\tilde{z}_t)/\hat{\sigma}_z)} \right], \quad (\text{A11})$$

$$\tilde{\Omega}_t = \Omega(\tilde{z}_t) \equiv \Phi(\log(\tilde{z}_t)/\sigma_z), \quad (\text{A12})$$

where $\Phi(\cdot)$ is the standard Normal c.d.f. The first four equations are optimal conditions for capital accumulation, job creation, capital utilization and job destruction, respectively. The auxiliary variable k_h denotes "effective" capital and is only introduced to shorten other equations in this appendix (in our numerical solution we do not solve for this variable). Equation (A9) is equal to $\int_{\tilde{z}}^{\infty} z l(\cdot, z) d\Omega(z|z > \tilde{z})$ in equation (24). Expression (A10) is the conditional expectation of z given $z > \tilde{z}_t$. It follows from the properties of the log-normal distribution. Similarly, equation (A11) is the conditional mean of $z^{\frac{(1-\psi)(1-\sigma)}{\psi\sigma - \psi - \sigma}}$. Notice that $\frac{(1-\psi)(1-\sigma)}{\psi\sigma - \psi - \sigma} \log z$ has standard deviation $\hat{\sigma}_z = \frac{(1-\psi)(1-\sigma)\sigma_z}{\psi\sigma - \psi - \sigma}$.

From the consumer's problem we have:

$$Q_t = \beta e^{\gamma_{yt}(\psi(1-\sigma)-1)} E[\lambda_{t+1}/\lambda_t], \quad (\text{A13})$$

$$\lambda_t = \psi C_t^{\psi(1-\sigma)-1} (N_t \bar{x}_t + U_t), \quad (\text{A14})$$

where

$$\bar{x}_t = \hat{z}_t \left[\frac{\lambda_t}{(1-\psi)C_t^{\psi(1-\sigma)}} (1-\alpha) e^{\zeta_t} k_{ht}^{\alpha} \right]^{\frac{(1-\psi)(1-\sigma)}{\psi\sigma - \psi - \sigma}} \quad (\text{A15})$$

is an auxiliary variable representing the term $\int_{\tilde{z}}^{\infty} (1-l(\cdot, z))^{\psi(1-\sigma)-1} d\Omega(z|z > \tilde{z})$ in equation (27). We get this expression by operating on the hours equation (37). First, we get leisure time

$$1 - l_t(\cdot, z) = \left[\frac{\lambda_t}{(1-\psi)C_t^{\psi(1-\sigma)}} (1-\alpha) e^{\zeta_t} k_{ht}^{\alpha} z \right]^{\frac{1}{\psi\sigma - \psi - \sigma}}.$$

Then, we raise both sides of this equality to $(1 - \psi)(1 - \sigma)$ and take conditional expectation with respect to z , we obtain (A15).

We now define three other variables that show up in the firm's optimal conditions and need to be solve for: the average wage $\bar{w}_t$, the minimum/marginal wage $\tilde{w}_t$, and the marginal hours $\tilde{l}_t$. After manipulating the hours worked and wage equations (37) and (38), we get

$$\bar{w}_t = (1 - \eta) \left\{ \frac{C_t^{\psi(1-\sigma)}(1 - \bar{x}_t)}{(1 - \sigma)\lambda_t} + \frac{e^{\gamma_{yt}b}}{\lambda_t} \right\} + \eta \left\{ (1 - \alpha)e^{\zeta_t} k_{ht}^\alpha \bar{l}_{zt} + e^{\gamma_{yt}} \kappa \theta_t \right\}, \quad (\text{A16})$$

$$\begin{aligned} \tilde{w}_t = (1 - \eta) \left\{ \frac{C_t^{\psi(1-\sigma)}[1 - (1 - \tilde{l}_t)^{(1-\psi)(1-\sigma)}]}{(1 - \sigma)\lambda_t} + \frac{e^{\gamma_{yt}b}}{\lambda_t} \right\} \\ + \eta \left\{ (1 - \alpha)e^{\zeta_t} k_{ht}^\alpha \tilde{z}_t \tilde{l}_t + e^{\gamma_{yt}} \kappa \theta_t \right\}, \end{aligned} \quad (\text{A17})$$

$$\tilde{l}_t = 1 - \left[\frac{\lambda_t}{(1 - \psi)C_t^{\psi(1-\sigma)}} (1 - \alpha)e^{\zeta_t} k_{ht}^\alpha \tilde{z}_t \right]^{\frac{1}{\psi\sigma - \psi - \sigma}}. \quad (\text{A18})$$

Another key equation is the law of motion for employment N_t . We define it below together with separation probability ρ_t , the unemployment rate U_t , the job finding probability j_t , the labor market tightness θ_t , and the job matching probability q_t , as follows

$$N_{t+1} = (1 - \rho_t)N_t + j_t U_t, \quad (\text{A19})$$

$$\rho_t = \tilde{\Omega}_t(1 - \bar{\rho}) + \bar{\rho}, \quad (\text{A20})$$

$$U_t = 1 - N_t, \quad (\text{A21})$$

$$j_t = (1 - \tilde{\Omega}_t)\theta_t q_t, \quad (\text{A22})$$

$$\theta_t = V_t/U_t, \quad (\text{A23})$$

$$q_t = 1/(1 + \theta_t^\varphi)^{1/\varphi}, \quad (\text{A24})$$

We now define the resources constraint of the economy which must be satisfied in

equilibrium as well as other aggregate variables such as total output Y_t , investment I_t , output per worker y_t , and total hours H_t :

$$Y_t = C_t + I_t + e^{\gamma_{yt}} \kappa V_t, \quad (\text{A25})$$

$$Y_t = e^{\zeta_t} k_{ht}^\alpha L_t, \quad (\text{A26})$$

$$I_t = e^{\gamma_{yt} + \gamma_{vt}} K_{t+1} - (1 - \delta_t) K_t / e^{\gamma_{vt}}, \quad (\text{A27})$$

$$y_t = Y_t / N_t, \quad (\text{A28})$$

$$H_t = N_t \bar{l}_t, \quad (\text{A29})$$

where

$$\bar{l}_t = 1 - \hat{z}_t \left[\frac{\lambda_t}{(1 - \psi) C_t^{\psi(1 - \sigma)}} (1 - \alpha) e^{\zeta_t} k_{ht}^\alpha \right]^{\frac{1}{\psi\sigma - \psi - \sigma}} \quad (\text{A30})$$

is the average hours per worker, and

$$\hat{z}_t = \exp \left[\underbrace{\left(\frac{\sigma_z}{\psi\sigma - \psi - \sigma} \right)^2}_{\hat{\sigma}} / 2 \right] \left[\frac{\Phi(\hat{\sigma}_z - \log(\tilde{z}_t) / \hat{\sigma}_z)}{\Phi(-\log(\tilde{z}_t) / \hat{\sigma}_z)} \right] \quad (\text{A31})$$

is an auxiliary variable representing the conditional mean of $z^{\frac{1}{\psi\sigma - \psi - \sigma}}$.

Finally, the stochastic processes for ζ_t , γ_{vt} and γ_{yt} ,

$$\zeta_{t+1} = \rho_\zeta \zeta_t + \nu_{\zeta t+1}, \quad (\text{A32})$$

$$\gamma_{vt+1} = (1 - \rho_v) \gamma_v^* + \rho_v \gamma_{vt} + \nu_{vt+1}, \quad (\text{A33})$$

$$\gamma_{yt} = \gamma_y^* + \alpha / (1 - \alpha) (\gamma_{vt} - \gamma_v^*), \quad (\text{A34})$$

where the innovations $\nu_{\zeta t}$ and ν_{vt} are Normal *iid* as described in the model section.

The last equation comes from (14) and the fact that the average growth rate of output

is $\gamma_y^* = \gamma_\phi^* + (\alpha / (1 - \alpha)) \gamma_v^*$ due to Cobb-Douglas technology.

A.2 Steady state equations

From the previous equations we can derive the non-stochastic steady state of the economy, which we use to calibrate the model. Recall that we normalize $h^* = 1$ by appropriately choosing parameters ω and ξ (for more details, see the calibration section).

- Firm's and consumer's optimality conditions:

$$1 = Q^* \left[\alpha k^{*\alpha-1} + \frac{1 - \delta^*}{e^{\gamma_v^*}} \right], \quad (\text{A35})$$

$$\frac{\kappa}{q^*} = Q^* \left\{ (1 - \Omega(\tilde{z}^*)) \left[(1 - \alpha) k^{*\alpha} \bar{l}_z^* - \bar{w}^* + e^{\gamma_y^*} (1 - \bar{\rho}) \frac{\kappa}{q^*} \right] \right\}, \quad (\text{A36})$$

$$\tilde{w}^* = (1 - \alpha) k^{*\alpha} \tilde{z}^* \tilde{l}^* + e^{\gamma_y^*} (1 - \bar{\rho}) \frac{\kappa}{q^*}, \quad (\text{A37})$$

$$Q^* = \beta e^{\gamma_y^* (\psi(1-\sigma)-1)}, \quad (\text{A38})$$

$$\lambda^* = \psi C^{*\psi(1-\sigma)-1} (N^* \bar{x}^* + U^*). \quad (\text{A39})$$

- Unemployment and other related variables:

$$U^* = \frac{\rho^*}{\rho^* + (1 - \Omega(\tilde{z}^*)) \theta^* q^*}, \quad (\text{A40})$$

$$\rho^* = \Omega(\tilde{z}^*) (1 - \bar{\rho}) + \bar{\rho}, \quad (\text{A41})$$

$$q^* = 1 / (1 + \theta^{*\varphi})^{1/\varphi}, \quad (\text{A42})$$

$$\theta = V^* / U^*, \quad (\text{A43})$$

$$N^* = 1 - U^*. \quad (\text{A44})$$

- Resource constraint and other related variables:

$$Y^* = C^* + I^* + e^{\gamma_y^*} \kappa V^*, \quad (\text{A45})$$

$$Y^* = k^{*\alpha} L^*, \quad (\text{A46})$$

$$I^* = [e^{\gamma_y^* + \gamma_v^*} - (1 - \delta^*) / e^{\gamma_v^*}] K^*. \quad (\text{A47})$$

- Other variables:

$$\delta^* = \xi/\omega, \quad (\text{A48})$$

$$k^* = K^*/L^*, \quad (\text{A49})$$

$$L^* = N^* \bar{l}_z^*, \quad (\text{A50})$$

$$\bar{l}_z^* = \bar{z}^* - \hat{z}^* \left[\frac{\lambda^*}{(1-\psi)C^{*\psi}(1-\sigma)} (1-\alpha)k^{*\alpha} \right]^{\frac{1}{\psi\sigma-\psi-\sigma}}, \quad (\text{A51})$$

$$\bar{x}^* = \hat{z}^* \left[\frac{\lambda^*}{(1-\psi)C^{*\psi}(1-\sigma)} (1-\alpha)k^{*\alpha} \right]^{\frac{(1-\psi)(1-\sigma)}{\psi\sigma-\psi-\sigma}}, \quad (\text{A52})$$

$$\bar{w}^* = (1-\eta) \left\{ \frac{C^{*\psi}(1-\sigma)(1-\bar{x}^*)}{(1-\sigma)\lambda^*} + \frac{e^{\gamma_y^*} b}{\lambda^*} \right\} + \eta \left\{ (1-\alpha)k^{*\alpha} \bar{l}_z^* + e^{\gamma_y^*} \kappa \theta^* \right\}, \quad (\text{A53})$$

$$\begin{aligned} \tilde{w}^* = (1-\eta) \left\{ \frac{C^{*\psi}(1-\sigma)[1-(1-\tilde{l}^*)(1-\psi)(1-\sigma)]}{(1-\sigma)\lambda^*} + \frac{e^{\gamma_y^*} b}{\lambda^*} \right\} \\ + \eta \left\{ (1-\alpha)k^{*\alpha} \tilde{z}^* \tilde{l}^* + e^{\gamma_y^*} \kappa \theta^* \right\}, \quad (\text{A54}) \end{aligned}$$

$$\tilde{l}^* = 1 - \left[\frac{\lambda^*}{(1-\psi)C^{*\psi}(1-\sigma)} (1-\alpha)k^{*\alpha} \tilde{z}^* \right]^{\frac{1}{\psi\sigma-\psi-\sigma}}, \quad (\text{A55})$$

$$\bar{l}^* = 1 - \hat{z}^* \left[\frac{\lambda^*}{(1-\psi)C^{*\psi}(1-\sigma)} (1-\alpha)k^{*\alpha} \right]^{\frac{1}{\psi\sigma-\psi-\sigma}}, \quad (\text{A56})$$

$$\bar{z}^* = \exp(\sigma_z^2/2) \left[\frac{\Phi(\sigma_z - \log(\tilde{z}^*)/\sigma_z)}{\Phi(-\log(\tilde{z}^*)/\sigma_z)} \right], \quad (\text{A57})$$

$$\hat{z}^* = \exp \left[\left(\frac{(1-\psi)(1-\sigma)\sigma_z}{\psi\sigma-\psi-\sigma} \right)^2 / 2 \right] \left[\frac{\Phi(\hat{\sigma}_z - \log(\tilde{z}^*)/\hat{\sigma}_z)}{\Phi(-\log(\tilde{z}^*)/\hat{\sigma}_z)} \right], \quad (\text{A58})$$

$$\hat{\tilde{z}}^* = \exp \left[\left(\frac{\sigma_z}{\psi\sigma-\psi-\sigma} \right)^2 / 2 \right] \left[\frac{\Phi(\hat{\sigma}_z - \log(\tilde{z}^*)/\hat{\sigma}_z)}{\Phi(-\log(\tilde{z}^*)/\hat{\sigma}_z)} \right]. \quad (\text{A59})$$

A.3 Existence of the productivity threshold $\tilde{z}$

We claim that all matches with $z < \tilde{z}$ are inefficient (i.e., non-profitable) and, therefore, destroyed. Here we provide an heuristic proof of that claim. First, let us write the right hand side of the job destruction equation (25) as a function of z . That is,

$$RHS(z) = (1-\alpha)e^\zeta f(\hat{k}h)z l(z) + \frac{e^{\gamma_y} \kappa (1-\bar{\rho})}{q(\theta)}. \quad (\text{A60})$$

Recall that the last term of (25) is zero. Similarly, the LHS of the job destruction condition as a function of z is simply the wage equation (38), which we reproduce below (with somewhat simplified notation)

$$w(z) = (1 - \eta) \left\{ \frac{\hat{c}^{\psi(1-\sigma)} [1 - (1 - l(z))^{(1-\psi)(1-\sigma)}]}{(1 - \sigma)\lambda} + \frac{e^{\gamma_y} b}{\lambda} \right\} + \eta \left\{ (1 - \alpha) e^{\zeta} f(\hat{k}h) z l(z) + e^{\gamma_y} \kappa \theta \right\}.$$

It should be clear that if $RHS(z) < w(z)$, then the marginal value for the firm of a match with productivity z is lower than its marginal cost (i.e., the wage), in which case the match is not profitable. That is, the firm is better off laying off that worker and opening a vacancy at cost $e^{\gamma_y} \kappa$. Notice that the second term of $RHS(z)$ takes into account the future expected value of not laying off a worker. Thus, a necessary condition for a threshold $\tilde{z}$ to exist is that for sufficiently small values of z , the inequality $RHS(z) < w(z)$ is satisfied. Let us take the limit of $RHS(z)$ and $w(z)$ as $z \rightarrow 0$, which we denote RHS_0 and w_0 , respectively. We obtain the following expressions:

$$RHS_0 = \frac{e^{\gamma_y} \kappa (1 - \bar{\rho})}{q(\theta)}, \quad (\text{A61})$$

$$w_0 = (1 - \eta) \frac{e^{\gamma_y} b}{\lambda} + \eta e^{\gamma_y} \kappa \theta. \quad (\text{A62})$$

Given that we do not have closed-form solution of the equilibrium allocation and, in particular, for θ and λ , as a function of the state variables (as well as primitives), it is not possible to demonstrate that $RHS_0 < w_0$ in all states. However, we do make sure that this condition is satisfied both in the steady state and in the numerical solution of the dynamic model.

Another necessary condition for equation (25) to have a solution is that for sufficiently large z , $RHS(z) > w(z)$. We prove that as follow. It is sufficient to show that

there is some $\hat{z}$ such that for all $z > \hat{z}$, $\partial RHS(z)/\partial z > \partial \hat{w}(\cdot, z)/\partial z$. These derivatives are

$$RHS'(z) = (1 - \alpha)e^\zeta f(\hat{k}h)[l(z) + zl'(z)], \quad (\text{A63})$$

$$w'(z) = (1 - \eta) \left\{ \frac{\hat{c}^{\psi(1-\sigma)}(1 - \psi)l'(z)}{\lambda} \right\} + \eta \left\{ (1 - \alpha)e^\zeta f(\hat{k}h)[l(z) + zl'(z)] \right\}. \quad (\text{A64})$$

Notice that $l(z)$ - see equation (37) - is bounded above at 1 and monotonically increasing in z . Thus, let us pick $\hat{z}$ sufficiently large such that $l(\hat{z})$ is sufficiently near 1, and consequently its derivative $l'(\hat{z})$ is small enough so that $RHS'(\hat{z}) > w'(\hat{z})$. This inequality holds because the first term on the right of (A64) becomes negligible and the second term is a fraction η of $RHS'(z)$. It is clear that this inequality holds for all $z > \hat{z}$.

These two necessary conditions together guarantee that $\tilde{z}$ exists. From here it is easy to see that, for each state, $\tilde{z}$ is unique.

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