Medium–Term Cycles and Labor-Market Search[☆]

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Abstract

New technologies create new jobs as well as destroy old ones. At the same time, the incentives to innovate the production technology are likely affected by the conditions on the labor market. What does this imply for the medium-term fluctuations in unemployment and job vacancies? What role do labor market frictions play for R&D and new technology adoption? To address these issues, we embed an R&D sector in a standard real business cycle model with search and matching frictions in the labor market. The technology in the model is thus endogenous. We first document the medium-term cycle properties of key labor market variables. Then we put the model to the twin test of generating the observed high– and medium–frequency fluctuations in vacancies and unemployment in response to shocks to the innovation process of a plausible magnitude (Shimer's puzzle). We also study how innovation respond to changes in the labor market frictions.

Keywords: Labor market dynamics, Medium–term cycles, R&D.
JEL: E24, E32, O32

1. Introduction

The study of the macroeconomic implications of technological progress on the labor market dynamics has been dominated by two theoretical frameworks in recent research: the endogenous growth models, see e.g. Aghion and Howitt (1994) among others, and the matching models, see e.g. the textbook by Pissarides (2000). In addition, there is no clear consensus on the macroeconomic implications of technological change on labor market variables. On the one hand, technological progress reduces unemployment by improving labor productivity and therefore increasing the profit due to job creation in Pissarides (2000, Chap. 2).[1] On the other hand, technological progress can increase unemployment both directly, by raising the job separation rate, and indirectly, by discouraging the creation of job vacancies in Aghion and Howitt (1994). How does technological change affect both the high– and medium–frequency fluctuations of unemployment and job vacancies? This paper provides an alternative approach that unifies the two previous approaches by embedding endogenous growth by expanding input varieties and labor market frictions in a standard real business cycle model. The outcome is a tractable dynamic general equilibrium model that can be used to analyze both the high– and medium–frequency comovements between key labor market variables and technological change. The conventional view is that old jobs are destroyed when new technologies arrive and, at the

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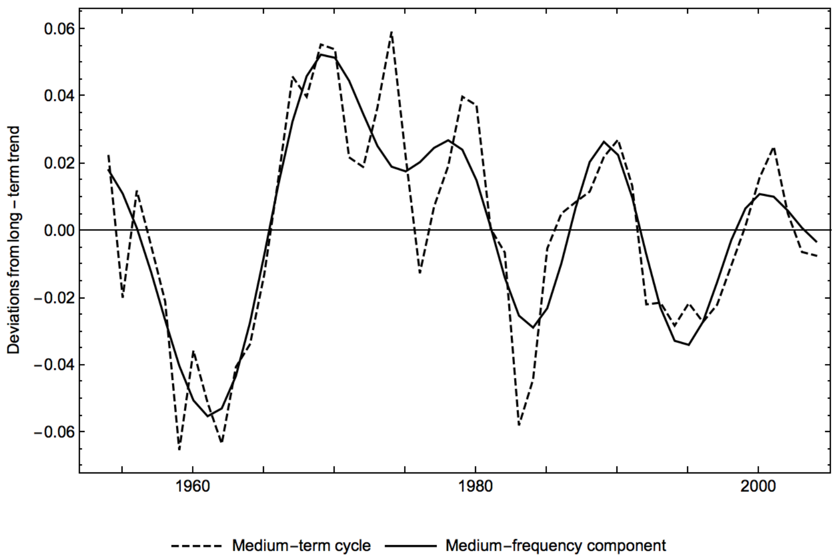
[1] This is the so-called *capitalization* effect.

same time, technological change create new more productive employment opportunities (Mortensen and Pissarides, 1998, p. 734). Subsequently, it is crucial to understand how new technologies affect key labor market variables such that unemployment, job vacancies or wage both in the short term (high–frequency) and long term (medium–frequency). This paper attempts to address this question.

Numerical analysis on the calibrated model offer two main results. First, The elasticity of v–u ratio with respect to net labor productivity critically depends on the steady state growth of the innovation possibility frontier and inverse of elasticity of substitution between varieties. This setup tributary to the medium–term matching model constitute a plausible channel to solve a part of the Shimer puzzle. Second, in reaction to the the innovation shock the marginal product of R&D decreases and marginal product of physical capital increases. Response of job vacancies depends on the elasticity of the final good with respect to R&D output. When the production function in the final good sector is less intensive in R&D output, firms tend to open more vacancies.

Figure 1: US per capita output in the medium–term. Data 1953–2003



Macroeconomic variables, such as GDP or unemployment exhibit fluctuations around their long-term trends that are both large and persistent (Blanchard and Summers, 1987; Stock and Watson, 1999). Furthermore, these variables fluctuate significantly not only at the high–frequency usually defined as fluctuations with periodicity between 2 and 32 quarters (Burns and Mitchell, 1946), but also at the medium–frequency which reflects fluctuations with periodicity between 32 and 200 quarters (Evans et al., 1998).

Figure 1 plots the medium–term cycle for the U.S per capita output between 1953 and 2003. The dashed line gives the percent deviation of per capita output from the trend for the medium–term cycle. The solid line gives the medium–frequency component. The difference between the two lines is the high–frequency component which corresponds to the conventional measure of the cycle in the business cycle literature.

Since medium–frequency oscillations seem to be intimately related to the high–frequency output fluctuations, it is important to modify the standard trend/cycle decomposition approach in order to be able to generate new stylized facts concerning medium–term fluctuations (Comin and Gertler, 2006). Thus, we first consider a suitable trend/cycle decomposition which includes in the measure of the cycle both the high– and medium–

frequency variation. Second, we develop a medium-term business cycles model with search and matching frictions. Finally we use the model to investigate how new technologies affect the short- and medium–run characteristics of the labor market dynamics. More specifically, we evaluate the model's ability to account for the observed high– and medium–frequency fluctuations of v–u ratio in response to shocks of a plausible magnitude (*Shimer's (2005) puzzle*).

The paper is linked with three main literatures. First, our paper is related to the literature of labor markets with search and matching frictions (Mortensen and Pissarides, 1994; Merz, 1995; Andolfatto, 1996; Nakajima, 2012; Elsby and Michaels, 2013). These papers address the business cycle fluctuations of the labor market, while our paper focus both on the business– and medium–frequency fluctuations. Second, our work has many points in common with the recent literature which argues that medium–term fluctuations can be explained by the same factors as business cycle fluctuations (Comin and Gertler, 2006; Comin et al., 2014; Schwark, 2014; Anzoategui et al., 2016). Contrary to these studies, our paper takes into account interactions between new technologies and labor market frictions. Third, our paper is also broadly related to the work of Stadler (1990); Aghion and Saint-Paul (1998a,b); Jones et al. (2000); Fiaschi and Sordi (2002); Bianchi and Kung (2014), who study the relationship between business cycle fluctuations and long-term growth. These papers introduced endogenous growth into the real business cycle models. Their approach follows seminal papers pioneered by Lucas (1988); Romer (1986, 1990); Barro (1990); Grossman and Helpman (1991) and Aghion and Howitt (1992). Within these theoretical frameworks, short-term shocks affect the profitability of production activity and influence the incentives to innovate and develop new products. Our paper exploits the same mechanism, especially the one developed in Rivera-Batiz and Romer (1991), to investigate the medium-term labor market dynamics.

The remainder of this paper is organized as follows. Section 2 documents empirical regularities about medium–term business cycles in the U.S labor market. Section 3 outlines the model. Section 4 discusses calibration and results. Finally, section 5 concludes.

2. Data

This section presents some empirical evidence about medium–term business fluctuations in the U.S labor market, which is based on a spectral decomposition of the time series. We used two kinds of database: (i) the U.S federal agencies database such that the Bureau of Labor Statistics or the National Science Foundation and (ii) the Shimer database (See Appendix H, Table H.1, for details.)

To detrend the data, we use a band pass filter, see e.g. Baxter and King (1999). A popular alternative is the Hodrick and Prescott (1997) filter. However a band pass filter allows to be precise in frequency domain terms.

The evolution of the U.S unemployment rate between 1953 and 2003 is a good illustration of the medium–term business cycles (see Appendix H, Figure H.1, for details.) The U.S unemployment rate was relatively low in the 50s and 60s, then increased for roughly next 15 years and then, since the 90s, went back to the lower levels. These fluctuations occur with periodicity far greater than a decade and are rather attributed to the medium frequency component of the medium term cycle. As documented in the literature, the unemployment rate is also subject to fluctuations in higher frequencies (Blanchard and Summers, 1987; Blanchard, 1997; Berentsen et al., 2011), and these are usually associated with booms and recessions. The shaded areas on Figure H.1 represent recession periods, announced by the National Bureau of Economic Research (NBER).

Figure 2 plots the medium–term cycle for R&D, TFP, unemployment and Labor productivity in the U.S. For each variable, the dashed line measures the percent deviation from trend for the medium–term cycle. The solid line gives the medium–term component, i.e. the variation in the data at frequencies between 32 and 200 quarters. The difference between the two lines is the high–frequency component, i.e. the variation at frequencies between 2 and 32 quarters which is the measure of the cycle in conventional analysis. Put differently, Graphs on Figure 2 confirm the intuition gained from the visual inspection of the non-detrended unemployment rate (See Appendix H, Figure H.1). First, there is substantial variation of unemployment in medium term frequencies. Second, the medium–term component seems very pronounced for the unemployment rate, but also for other key variables. Third, for each variable, there is a lot of variation in the data for frequencies between 2 and 32 quarters.

Figure 2: Medium–term and -frequency dynamics. Data 1953–2003

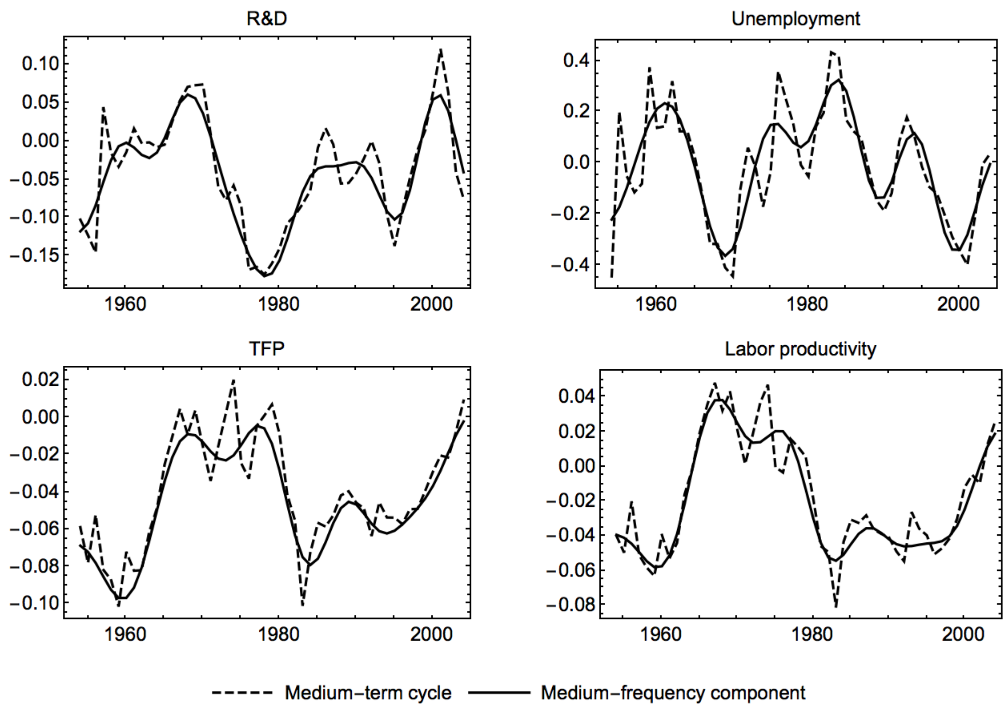


Table 1 presents a set of statistics of the medium–term cycles for R&D, TFP, unemployment and Labor productivity, which seem to be substantially more volatile than the conventionally measured high–frequency cycle. It also presents a similar set of statistics for per capita output and other traditional labor market variables. For each variable, the table reports the percent standard deviation over the medium–term cycle, and also the standard deviations of both the high– and medium–frequency components. Below each number are 95-percent confidence intervals.

In order to complete the descriptive analysis, Tables 2, 3 and 4 respectively show the comovement of the U.S unemployment rate, R&D and TFP with others key macroeconomic variables. In sum, the unemployment-vacancies comovement, calculated for the whole medium–term cycle amounts to around –0.65 and is higher in absolute terms for the higher frequency component of the cycle (around –0.91) than for the medium–term frequencies (–0.54).

Table 1: Standard deviations. Data 1953–2003

	Medium–term cycle	High–frequency component	Medium–frequency component
Frequencies	0–50	0–8	8–50
Output per capita	3.09 (2.59–3.84)	1.42 (1.19–1.76)	2.75 (2.30–3.42)
Total factor productivity	3.02 (2.52–3.75)	1.17 (0.98–1.45)	2.80 (2.34–3.48)
Research and development	7.14 (5.97–8.87)	2.85 (2.38–3.54)	6.34 (5.30–7.88)
Labor productivity	3.30 (2.76–4.10)	1.14 (0.95–1.41)	3.09 (2.59–3.84)
Unemployment	22.27 (18.64–27.69)	11.69 (9.78–14.53)	19.07 (15.96–23.71)
Vacancies	23.01 (19.25–28.60)	13.04 (10.91–16.21)	18.59 (15.55–23.10)
Labor market tightness	41.14 (34.42–51.13)	24.31 (20.34–30.22)	33.10 (27.70–41.15)
Finding	12.21 (10.22–15.18)	6.85 (5.73–8.52)	10.11 (8.46–12.57)
Separation	9.84 (8.23–12.23)	4.23 (3.54–5.26)	8.85 (7.40–11.00)

Table 2: Cross-correlations with unemployment. Data 1953–2003

	Medium–term cycle	High–frequency component	Medium–frequency component
Frequencies	0–50	0–8	8–50
GDP per capita	–0.70	–0.85	–0.6
Labor productivity	–0.38	–0.33	–0.41
Vacancies	–0.65	–0.91	–0.54
Tightness	–0.88	–0.97	–0.85
Finding	-0.92	–0.96	–0.90
Separation	0.78	0.73	0.82

Table 3: Cross-correlations with R&D. Data 1953–2003

	Medium–term cycle	High–frequency component	Medium–frequency component
Frequencies	0–50	0–8	8–50
GDP per capita	0.11	0.35	0.05
Labor productivity	–0.15	–0.03	0.21
Unemployment	–0.49	–0.45	–0.51
Vacancies	0.16	0.44	0.03
Tightness	0.34	0.46	0.28
Finding	0.40	0.49	0.36
Separation	–0.45	–0.09	–0.57

Table 4: Cross-correlations with TFP. Data 1953–2003

	Medium–term cycle	High–frequency component	Medium–frequency component
Frequencies	0–50	0–8	8–50
GDP per capita	0.79	0.81	0.78
Labor productivity	0.89	0.94	0.88
Unemployment	–0.46	–0.50	–0.46
Vacancies	0.42	0.63	0.40
Tightness	0.50	0.58	0.51
Finding	0.46	0.51	0.47
Separation	–0.35	–0.67	–0.27

3. The model

The model combines the real business cycle model and the expanding variety of inputs endogenous growth model of Romer (1990). The novelty is allowing for frictional labor market.

There are five types of agents: final good producers, intermediate good producers, innovators, households, and a government. There are three sectors: final goods, intermediate goods, and research and development (R&D).

3.1. Final goods sector

Firms in the final goods sector are identical and perfectly competitive. The final good is produced with the production function:

$$y = z^{1-\psi} \left[k^{\alpha} l^{1-\alpha}\right]^{\psi}, \tag{1}$$

where z is a constant elasticity of substitution (CES) aggregate of intermediate goods:

$$z = \left[\int_0^N x(i)^{1-\psi} \, \mathrm{d}i \right]^{\frac{1}{1-\psi}}, \tag{2}$$

and k and l are respectively inputs of capital services and labor. N denotes the number of varieties of intermediate goods available to be used in production in period t and $x(i)$ is the amount of variety i used in period t. $\epsilon_\psi \equiv 1/\psi$ is the elasticity of substitution between intermediate goods, and $0 < \alpha < 1$.

A representative final good producer buys intermediate goods, rents physical capital, and hires workers to maximize profits, taking the number of varieties N as given.[2] While intermediate goods and capital are available on spot markets, workers must be hired on the labor market one period in advance because of search and matching frictions. Capital depreciates at rate $\delta_k \in (0,1)$. Denote $V(l;N)$ the value function of the final good producer that hired l workers, $p(i)$ the price of intermediate good variety i, r the interest rate, w the wage rate, v the number of vacancies to be posted for the next period, and κ the per vacancy posting cost. Following Pissarides (2000, chap. 3), the firm's vacancy posting cost is assumed to be proportional to productivity. As will be seen later, the specification of the firm's recruitment cost ensures existence of a balanced growth path equilibrium with stationary free entry condition in the labor market. Let Ω be the set of variables that define the aggregate state such that $\Omega = (\eta, N, L, K, A)$, where η is a shock to innovation technology, L is the total number of workers hired for the current period, K is the aggregate amount of capital rented in the current period and A is the aggregate amount of R&D spending. Let $\beta E \Lambda(\Omega, \Omega')$ be the firm's discount rate, where the parameter β denotes the household's subjective discount factor. The problem of a final good producer reads:

$$\begin{aligned} V(l, \Omega) = \max_{x(i),k,l',v} \Big\{ & z^{1-\psi} \left[k^\alpha l^{1-\alpha}\right]^\psi - \int_0^N p(i)\, x(i)\, di - R\, k \\ & -\omega l - \kappa N'^{\frac{1}{1-\alpha}} v + \beta E \left\{ \Lambda\left(\Omega, \Omega'\right) V\left(l', \Omega'\right) | l, \Omega \right\} \Big\}, \end{aligned} \tag{3}$$

subject to (2) and the laws of motion of employment and aggregate variables and pricing:

$$l' = (1-\delta_l)\, l + q\, v \tag{4}$$

$$\eta' = G_\eta(\Omega) \tag{5}$$

$$N' = G_N(\Omega) \tag{6}$$

$$L' = G_L(\Omega) \tag{7}$$

[2] Equation (1) implies that when N types of intermediate goods are available at finite prices at the current time, the final good firm will be motivated to use all these N types.

$$K' = G_K(\Omega) \tag{8}$$

$$A' = G_A(\Omega) \tag{9}$$

$$p(i) = P(\Omega) \tag{10}$$

$$R = R(\Omega) \tag{11}$$

$$\omega = \tilde{W}(\Omega). \tag{12}$$

Here prime indicates the next period variable, δ_l is the job separation rate, and q is the probability of filling a vacancy.[3]

The decision rules for the final good producer are:

$$x(i) = g_{x(i)}(l, \Omega) \tag{13}$$

$$k = g_k(l, \Omega) \tag{14}$$

$$l' = g_l(l, \Omega) \tag{15}$$

$$v = g_v(l, \Omega). \tag{16}$$

The price of the final good is taken as the numeraire.

3.2. Intermediate goods sector and R&D

This section closely follows section 13.1 from Acemoglu (2009). Intermediate good firms operate in a monopolistically competitive setting. Production function for each existing variety i of intermediate goods is linear. Namely, one unit of variety i can be produced at constant marginal cost $\mu > 0$ units of the final good. New varieties can be invented by making R&D expenditures denoted by a. We assume free entry into the R&D sector, any firm or individual can initiate research. The inventor of the new variety

[3] If we want to incorporate variable utilization of capital, the production function will be modified to $y = z^{1-\psi}\left[(\nu k)^{\alpha} l^{1-\alpha}\right]^{\psi}$ for some utilization rate ν, whereas the net capital rental rate is still $r + \delta_k$. This effectively assumes the firm rents physical capital stock k and then decides internally how intensively it is going to use it in production. In equilibrium the net rental rate $r + \delta_k$ will adjust appropriately. Notice that this also assumes the capital stock depreciates even if not utilized.

receives a fully enforced perpetual patent on this variety. The aggregate level of knowledge (number of existing varieties) evolves according to:

$$N' = (1-\delta_N)\,N + \chi a' N, \tag{17}$$

where δ_N denotes the rate of obsolescence of technologies. The second term N on the right-hand side captures spillovers from the stock of existing ideas. The greater N is, the more productive are R&D expenditure. The economy starts with some initial knowledge stock $N_0 > 0$. We introduce a technology coefficient χ that implies a decreasing marginal benefit of innovation in capital:[4]

$$\chi = \eta K'^{-1}, \tag{18}$$

where η is a random shock to the innovation process.

The value of owning a patent for variety i is the value of expected discounted monopolistic profits:

$$W(i;\Omega) = \max_{p(i),x(i)} \left\{ p(i)\,x(i) - \mu x(i) + (1-\delta_N)\,\beta E\left\{\Lambda\left(\Omega,\Omega'\right) W\left(i;\Omega'\right)|\Omega\right\}\right\}, \tag{19}$$

where $x(i)$ is the final good sector's demand schedule for variety i. The decision rules for the intermediate good producer are:

$$p(i) = g_{p(i)}(\Omega) \tag{20}$$

$$x(i) = g_{x(i)}(\Omega). \tag{21}$$

The free entry into research sector implies that the marginal return to R&D expenditures must be equal to the opportunity cost of funds:

$$\chi N (1-\delta_N)\,\beta E\left\{\Lambda\left(\Omega,\Omega'\right) W\left(i;\Omega'\right)|\Omega\right\} = 1 + r'. \tag{22}$$

If the left hand side of (22) was greater than $1 + r'$, an infinite amount of resources would be allocated into R&D activities. As a result, LHS of (22) $> 1 + r'$ cannot hold in equilibrium. Contrariwise, if left hand side of (22) was lower than $1 + r'$, no resources would be devoted to R&D activities. Hence, the number of goods, N, would not change over time. This analysis focus on equilibria with positive R&D and, therefore, N is growing at all points in time. In these cases, Equation (22) holds for any time. Moreover, as mentioned earlier, the innovation process is subject to a random shock. η denotes uncertainty about the quantity of resources required to generate a new intermediate good. Random shock in the innovation process eliminates the smoothness at the aggregate level and induces variations of the growth rate around a long term trend. According to Kydland and Prescott (1982), these variations could be interpreted as fluctuations that occur in real business cycle models.

[4] In this way we ensure that R&D expenditure will grow at the same constant rate as output at a balanced growth path.

3.3. Households

We assume that the representative household consists of a continuum of members of measure unity, each of which can be either employed or unemployed. Because of search and matching frictions on the labor market household members have to secure their jobs one period in advance. As a result, at the beginning of each period fraction L of household members have a job, whereas the remaining fraction $1-L$ are unemployed and spend the period searching for a new job.

The representative household consumes, saves, and supplies labor services to maximize its expected inter-temporal utility, with $\beta \in (0,1)$ the time discount factor, subject to a budget constraint, the law of motion of capital stock and the law of motion of employment. The per period utility function $u(c)$ is strictly increasing, strictly concave, and satisfies the usual Inada conditions. Denote k the capital stock and a the stock of one-period bonds in household's possession. Let $Q(k,a,\Omega)$ be the household's value function. The household's problem can be written recursively as:

$$Q(k,a,\Omega) = \max_{c,k',a'} \left\{ u(c) + \beta E \left\{ Q(k',a',\Omega') \,|k,a,\Omega \right\} \right\} \tag{23}$$

subject to:

$$c + k' + a' = \omega L + b(1-L) + [R + (1-\delta_k)]k + (1+r)a + \Pi^f + T \tag{24}$$

$$L' = (1-\delta_l)L + f(1-L), \tag{25}$$

and subject to the laws of motion of aggregate variables (5), (6), (7), (8), (9), and to the pricing equations (10), (11) and (12).

Equation (24) is the budget constraint, where b is unemployment benefit, R is the capital rental rate, r is the interest rate, and T are lump-sum transfers from the government. We assume the household is the residual claimant of the profits generated by the firms in the final goods sector, Π^f. Equation (25) is the law of motion of employment, where $\delta_l \in (0,1)$ is exogeneous job destruction rate and f is the probability of finding a new job for the unemployed.

The decision rules for the households are:

$$c = g_c(k,a,\Omega) \tag{26}$$

$$k' = \tilde{g}_{k'}(k,a,\Omega) \tag{27}$$

$$a' = g_{a'}(k,a,\Omega). \tag{28}$$

3.4. Frictional labor market and wage determination

The labor market is characterized by search and matching frictions. Employment relationship consists of a worker and a final good producer which engage in production until the relationship is severed. As in Cahuc and Wasmer (2001) and Elsby and Michaels (2013), final good producers need to post job vacancies one period ahead of production in order to recruit workers. Then, at the beginning of the period, the firms simultaneously bargain wages with the employees and choose the level of capital used in production. In such framework, employment is a predetermined variable but the wage rate and capital are not predetermined.

Each job can be in one of two states, filled or vacant. On the household side, workers can be either unemployed and searching for a job or employed and producing. The total number of vacancies posted by the firms is v. The total number of employed workers in the household is L. Let $u \equiv 1 - L$ be the measure of the pool of unemployed workers searching for a job in period t. Following Mortensen and Pissarides (1994) we model the number of new hires, m, as a function of searching workers and vacancies:

$$m = m(v, u), \tag{29}$$

where $m(\cdot)$ is the matching function that is homogeneous of degree one, increasing in each of its arguments, concave, and continuously differentiable.

Let $\theta \equiv v/u$ be the labor market tightness. Then, the probability a searching worker finds a job in period t is:

$$f \equiv m(\theta, 1), \tag{30}$$

with $\partial f/\partial\theta > 0$. Similarly, the probability a final good producer fills a vacancy is:

$$q \equiv m(1, 1/\theta), \tag{31}$$

with $\partial q/\partial\theta < 0$. Both workers and final good producer take f and q as given.

When matched, the new worker and the firm engage in Nash bargaining game, in which the wage is determined. A realized job match yields some pure economic that is shared by the firm and the worker. Let H be the worker's surplus, J be the firm's surplus, and $\xi \in (0, 1)$ be the worker's bargaining power. Then the bargained wage is:

$$\omega = \arg\max_{\omega} G \left\{ H\left(\omega, \Omega\right), J\left(\omega, \Omega\right); \xi \right\}, \tag{32}$$

where $G(\cdot)$ is the joint surplus which can be written as a Nash product.[5] J and H are Lagrange multipliers on the laws of motion for labor (4) and (25) respectively. As in Gertler and Trigari (2009), J can be interpreted as the marginal value to the firm of having another worker. H can be interpreted as the marginal value of the job to the household.

Intuitively, the negotiated wage can be viewed as the weighted arithmetic mean of reservation wages. Now given the worker's relative bargaining power, ξ, the negotiated wage reads:

$$\omega = \xi\overline{\overline{\omega}} + (1 - \xi)\underline{\underline{\omega}}, \tag{33}$$

where $\overline{\overline{\omega}}$ denote the highest wage that the final good producer is willing to pay for each additional worker and $\underline{\underline{\omega}}$ denote the lowest wage at which an unemployed would be willing to accept a new job. In other words, when the firms surplus $J = 0$, $\omega = \overline{\overline{\omega}}$. In contrast when the workers surplus $H = 0$, $\omega = \underline{\underline{\omega}}$.

[5] If the production function had decreasing returns to scale, the bargained wage would also depend on the size of the firm as in Cahuc and Wasmer (2001), Elsby and Michaels (2013), and Acemoglu and Hawkins (2014). This follows from applying Stole and Zwiebel (1996) protocol, which generalizes the bargaining solution of Nash (1950) to settings with diminishing returns. The protocol properly takes into account that fewer workers imply a higher marginal product of labor in the firm, which can partially spill over into higher wages. However, this effect cancels out when the production function has constant returns to scale through adjustments in demands for other factors that are acquired on spot markets (in our case capital). For more details, see Cahuc and Wasmer (2001).

3.5. Government

Finally, the lump-sum transfers adjust to balance the government budget constraint:

$$T + (1 - L)\, b = 0, \tag{34}$$

where unemployment benefits, b, are given exogenously. This completes the set of model equations.

3.6. Characterization of Equilibrium

A recursive equilibrium is a collection of (i) value functions $\{V(l,\Omega), W(i,\Omega), Q(k,a,\Omega)\}$; (ii) policy functions $\{g_{x(i)}(l,\Omega), g_k(l,\Omega), g_l(l,\Omega), g_v(l,\Omega), g_{p(i)}(\Omega), g_c(k,a,\Omega), g_{k'}(k,a,\Omega), g_{a'}(k,a,\Omega)\}$; (iii) marginal values $\{J(\omega,\Omega), H(\omega,\Omega)\}$; (iv) the contract wage $\tilde{W}(\Omega)$; (v) the number of vacancies to be posted for the next period $v(\Omega)$; (vi) the interest rate $r(\Omega)$ and the capital rental rate $R(\Omega)$; (vii) R&D expenditures A'; (viii) aggregate spending on intermediate goods $e(\Omega)$; (ix) the government allocation $\{b(\Omega), T\}$; and (x) laws of motion $\{G_N(\Omega), G_L(\Omega), G_K(\Omega), G_A(\Omega)\}$ such that:

- $G_N(\Omega) = (1-\delta_n) N + \chi N [a(\Omega')]$
- $G_L(\Omega) = g_l(l,\Omega)$
- $G_K(\Omega) = g_k(l',\Omega') = \tilde{g}_{k'}(k,a,\Omega)$
- $G_A(\Omega) = g_{a'}(k,a,\Omega)$
- Policy functions solve the respective optimization problems
- A' satisfies the free entry condition (22) into research sector
- $\tilde{W}(\Omega)$ solves the bargain problem (32)
- The government budget is balanced, that is Equation (34) holds
- The final goods market clears: $y = c + K' - (1-\delta_t)K + A' + e + \kappa {N'}^{1/1-\alpha} v$.

3.7. Balanced growth path

Let us now characterize the balanced growth path of the economy. Without loss of generality let us normalize the marginal cost of the intermediate good producer to $\mu \equiv (1-\psi)^2$, so that:

$$y = N k^{\alpha} l^{1-\alpha}, \tag{35}$$

where the knowledge stock grow at a rate $g_N > 0$. Then by taking logs, and then first difference we get:

$$(\ln y' - \ln y) = (\ln N' - \ln N) + \alpha(\ln k' - \ln k) + (1-\alpha)(\ln l' - \ln l). \tag{36}$$

Along a balanced growth path labor will grow at a rate $g_l = 1$. Capital will grow at the same rate as output because the real interest rate is constant (real interest rate in the long run is tied to the capital/output ratio). Using these facts, we find:

$$(1-\alpha)(\ln y' - \ln y) = (\ln N' - \ln N). \tag{37}$$

This says that as long as we have expansion of the variety in the model, the economy does not converge to a steady state but keeps growing along a balanced growth path where output will grow at $1/(1-\alpha)$ the rate of knowledge stock. As a result, along the balanced growth path, output divided by the scaling factor $N^{1/(1-\alpha)}$ does not grow, i.e. it is stationary:

$$y' N'^{\frac{-1}{(1-\alpha)}} = y N^{\frac{-1}{(1-\alpha)}}. \tag{38}$$

Hence we can induce stationarity in the production function by dividing both sides of the Equation (35) by the scaling factor $N^{1/(1-\alpha)}$:

$$\begin{aligned} \widetilde{y} &= N^{\frac{-\alpha}{1-\alpha}} \left(\frac{k}{N^{\frac{1}{1-\alpha}}} \right)^{\alpha} N^{\frac{\alpha}{1-\alpha}} l^{1-\alpha} \\ &= \widetilde{k}^{\alpha} l^{1-\alpha}. \end{aligned} \tag{39}$$

On a balanced growth path output y, consumption c, capital k, wages w all grow at the constant gross growth rate $g_N^{1/(1-alpha)}$, where $g_N = N'/N > 0$. The interest rate r, transition probabilities f and q, labor market tightness θ, and labor l are constant on the balanced growth path. From Equations (4) and (25), constant employment and transition probabilities on the balanced growth path imply that vacancies v, and unemployment u, are also constant on the balanced growth path.

The key variables are the labor market tightness, θ, the wage, $\widetilde{\omega}$, the knowledge stock, $\widetilde{N}$, the value of owning a patent for variety,[6] $\widetilde{W}$, and of course the aggregate demand, $\widetilde{y}$, which depends on consumption, $\widetilde{c}$, capital stock, $\widetilde{k}$, expenditure on intermediate goods, $\widetilde{e}$, and R&D investment, $\widetilde{a}'$.

Along a balanced growth path (BGP), Labor market tightness θ is defined as the ratio of vacancies, v, over effective search by the unemployed, u. In his treatise on American and British technology in the nineteenth century, Habakkuk (1967) argues that labor scarcity and the search for labor-saving inventions were central determinants of technological progress. The labor scarcity (rising tightness labor market) increased wages, which in turn encouraged labor-saving technological change. From Equation (C.12), the Nash bargaining solution relates $\widetilde{\omega}$ positively to θ. Moreover, $\widetilde{\omega}$ varies positively with the productivity of labor. The latter varies positively with the innovation possibilities frontier. Kennedy (1964) argues that it is the form of the innovation possibilities frontier, rather than the shape of a given neoclassical production function, that determines the relative factor share. Acemoglu (2007) shows that these results generalize to models of technology adoption.

3.8. Functional forms

We assume that the representative household derives utility from consumption according to the utility function:

$$u(c) = \frac{c^{1-\sigma} - 1}{1-\sigma}, \tag{40}$$

where $\sigma > 0$ denotes the inverse of the intertemporal elasticity of substitution in consumption. As argued by King et al. (1988), this functional form of utility is compatible with balanced growth along the optimal steady state. The matching function is taken to be Cobb-Douglas with constant returns to scale:

$$m(v, u) = \gamma_m v^{1-\gamma} u^{\gamma}, \tag{41}$$

[6] Where $W = N\,W(i)$ is stationary ($\widetilde{W}$), but not $W(i)$.

where $0 < \gamma < 1$ denotes the matching elasticity with respect to unemployment. The parameter γ_m reflects the efficiency of the matching process. As shown by Petrongolo and Pissarides (2001), the Cobb-Douglas matching function with constant returns to scale is consistent with the empirical evidence.

4. Results

The numerical strategy to solve the model is similar to the computational approach used in the Uhlig (2001) toolkit. We first find the first order necessary conditions. Then we characterize the general equilibrium of the economy, calculate the steady state log-linearize the equilibrium system around a non-stochastic steady state, and calibrate the parameters. Next, we compute impulse responses and simulated moments.

The properties of the model are investigated by studying the BGP equilibrium conditions (see Appendix C for details). The model contains 21 equations and 21 endogenous variables. The model can be split into 4 blocks : RBC block ; Labor market; R&D bloc; Closing and stochastic component. Thus, four sets of parameters characterize the model, those describing: Household preferences and the technology of production $(\beta, \sigma, \alpha, \delta_k)$; the labor market dynamics $(b, \xi, \kappa, \gamma_m, \gamma, \delta_l)$; R&D activities (ψ, δ_N); and the stochastic distribution of the exogenous shocks $(\rho_\eta, \sigma_\varepsilon)$. There is a total of 14 parameters.

Since our equilibrium features a goods, a labor and a R&D sector, the calibration targets characteristics of each sector. The model is calibrated to the United States for the period 1953–2003, with a time period to correspond to a year. We use the restrictions of balanced growth to pin down parameter values. The calibrated parameters are summarized in Table 5.

4.1. Calibration

The standard RBC parameters are set so that $\beta = 0.96$ (the discount factor), $\alpha = 0.33$ (the capital share), and $\delta_k = 0.096$ (the depreciation rate). A value of 1 is chosen for σ, implying a logarithmic utility function. Following Shimer (2005), the elasticity of the matching function, γ, takes the value 0.72. The share of a match surplus that the worker receives is set to 0.72. We assume an efficient benchmark equilibrium (Hosios, 1990).[7] Following Hall and Milgrom (2008), we conservatively set the unemployment benefits $b = 0.25$. As argued by Pissarides (2009), Ljungqvist and Sargent (2015) among others, a high value of b can help the standard matching model to solve dubiously the Shimer puzzle by generating high values of the v–u ratio with respect to deviation of productivity from unemployment benefits.[8] Based on evidence in Comin and Gertler (2006), we fix $\delta_N = 0.03$, which implies an annual obsolescence rate of three percent. In order to compare the predictions of the model to the results from the data, we set the steady-state unemployment rate equal to 0.058. It corresponds to the average of the U.S. unemployment rate over the period 1953-2003 in the Shimer data.

Given those choices, the matching efficiency parameter, γ_m, is used to assign the value 0.7 to the vacancy filling probability (again, based on a U.S. calibration).

We use the steady state restriction to pin down ψ, the inverse of elasticity of substitution between differentiated goods. We set $\psi = 1.3419$, implying a steady state k-y ratio equal to 2.4607. It corresponds to the average of the the U.S.capital-output ratio over

[7] It is to be noticed, however, there is no a priori reason that the equilibrium be necessary efficient in our setup, because of the distortions brought by monopolistic competition in the R&D sector.

[8] See Technical Appendix Appendix G.1 for details

Table 5: Baseline calibration.

1. External Calibration			
Parameter	Description	Value	Source
α	Capital share in the output	1/3	National Income (BLS)
σ	Relative risk aversion	1	Log-utility (standard)
δ_k	Capital depreciation rate	0.096	∼10% deprec. per annum
γ	Elasticity of matching function	0.72	Shimer (2005)
ξ	Workers' bargaining power	0.72	Shimer (2005)
b	Unemployment benefits	0.25	Hall and Milgrom (2008)
κ	Vacancy posting cost	0.3182	Station. entry and wage Eq. (D.10), (D.11), (D.13)
δ_N	Technology depreciation rate	0.03	Comin and Gertler (2006)
ρ_η	Persistence of η shocks	0.99	Transitory shock
σ_η	Dispersion of η process	0.01	g_N increases by 1%

2. Internal Calibration				
Parameter	Target (U.S. data, 1953-2003)	Value	Data	Model
β	Annual real interest rate (%)	0.9606	5.24	5.24
δ_l	Average job-finding	0.0269	0.44	0.44
γ_m	Average unemployment rate	0.5011	0.06	0.06
g_N	Gross output growth rate	1.0073	1.02	1.01
ψ	Capital-output ratio	0.0955	2.46	2.46

the period 1953-2003 in the Accounts from Bureau of Economic Analysis (BEA). We use the separation rate δ_l to pin down the average job-finding rate. From the Shimer data, a worker finds a job with $f = 0.44$. As a result, $\delta_l = 0.0269$, which is relatively close to the value of the separation rate for the period 1953-2003 in the Shimer data. We use the steady state matching function to pin down the matching efficiency coefficient γ_m. Finally, we use entry condition and wage equation, (D.10), (D.11), (D.13) respectively, in the steady state free to determine the vacancy posting cost $\kappa = 0.3182$.

The stochastic law of motion η for the innovation possibilities frontier evolves according to stationary AR(1) process:

$$\ln \eta = (1 - \rho_\eta) \ln \overline{\eta} + \rho_\eta \ln \eta_{-1} + \varepsilon_\eta, \tag{42}$$

where $|\rho_\eta| < 1$ denotes the persistence of the knowledge shock, $\varepsilon_\eta \sim$ i.i.d.$(0, \sigma_\varepsilon)$, and $\sigma_\varepsilon > 0$ denotes the dispersion of the stochastic process.

4.2. Simulations

We compute impulse response functions (IRFs) under a stationary shock with $\rho_\eta = 0.99$. We set the size of the transitory shock to 0.01, so the innovation possibilities frontier increases by one percent. In other words, we hitting the economy with a smaller initial shock.

Figure 3: IRFs for a shock to innovation possibilities frontier

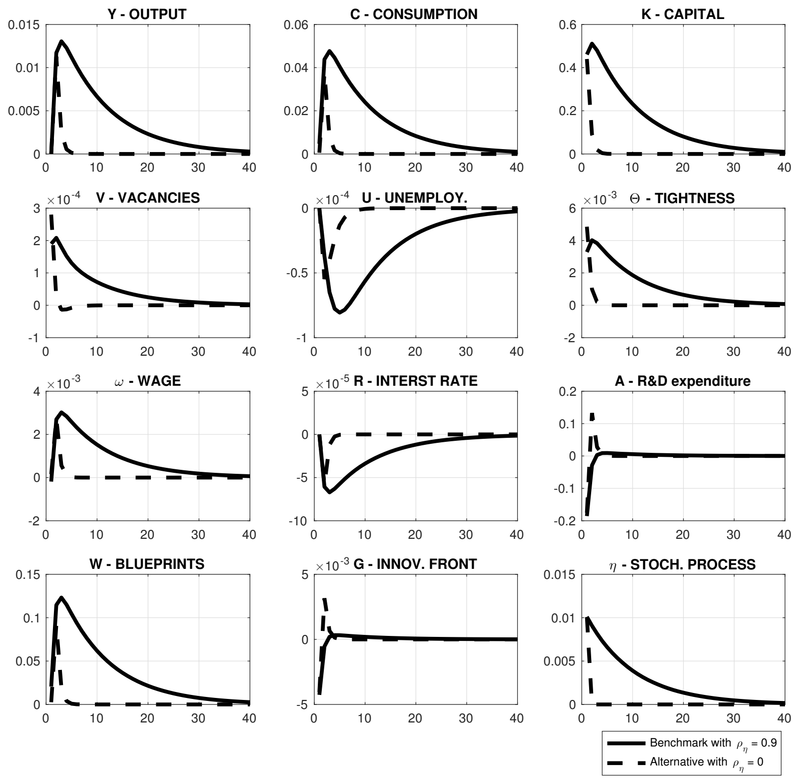


Figure 3 shows the response of output, consumption, capital, vacancies, unemployment, tightness, wage, interest rate, R&D expenditure, blueprints value and growth of the innovation possibility frontier to a one percentage point positive innovation possibilities frontier shock in the model.

In reaction to the the innovation shock the marginal product of investing in R&D decreases. The intuition for this result is the following. First consider the growth equation of the innovation possibilities frontier (g_N), see Eq. (C.20) in Appendix C. For a constant ratio (a'/k'), a positive shock on η increases g_N. Then, a rise of g_N, synonymous with more competition among the intermediate goods producers (because we now have more varieties than before), reduces the future value of blueprints. As a result the current value of blueprints also decreases, see Eq. (C.3). In other words, from a household's point of view, a positive shock on η makes capital investment (k') more attractive than R&D investment (a'), which explains a rise of k' and a decrease of a'. By the equation (C.5), an increase of k implies a lower interest rate (r) in the following period.

Moreover, the technological progress makes labor more productive in the next period, leading to an increase vacancy posting cost by Eq. (C.9–C.11). As a result the negotiated wage rate goes up. However, in our model, the response of job vacancies critically depends on the elasticity of the production function with respect to intermediate goods. When ψ tends to one, production function is less intensive in intermediate goods (R&D output), see Eq. (1), and firms tend to open more vacancies.

4.3. The Shimer puzzle in a medium-term matching model

In our model, the deviation of productivity from unemployment benefits or simply net labor productivity takes an analytical form which differs from that in the standard matching model because of the R&D sector and the Cobb-Douglas technology.

To evaluate the model's ability to account for the strong procyclicality of the v–u ratio with the weak procyclicality of labor productivity, we proceed as in Shimer (2005). We combine the job creation condition and the wage equation to characterize the sensitivity of the v–u ratio to deviation of productivity from unemployment benefits in the steady state. Thus we obtain the elasticity of labor market tightness with respect to net labor productivity (see Appendix G.1 for details):

$$\begin{aligned}\varepsilon_{\theta,p} &= \left\{ \frac{(1-\xi)\left[(1-\alpha)\,\psi\left(\overline{y}/\overline{l}\right)-\overline{b}\right]}{\left[\xi-\left(\frac{1-\beta}{\beta}+\delta_l\right)\frac{q'(\overline{\theta})}{q(\overline{\theta})^2}\right]\kappa\overline{\theta}} \right\} \overline{g}_N^{\frac{-1}{1-\alpha}} \\ &= \left\{ \frac{\beta^{-1}(1-\beta)+\delta_l+\xi f(\overline{\theta})}{\left[\beta^{-1}(1-\beta)+\delta_l\right](1-\varepsilon_{f,\theta})+\xi f(\overline{\theta})} \right\} \overline{g}_N^{\frac{-1}{1-\alpha}},\end{aligned} \tag{43}$$

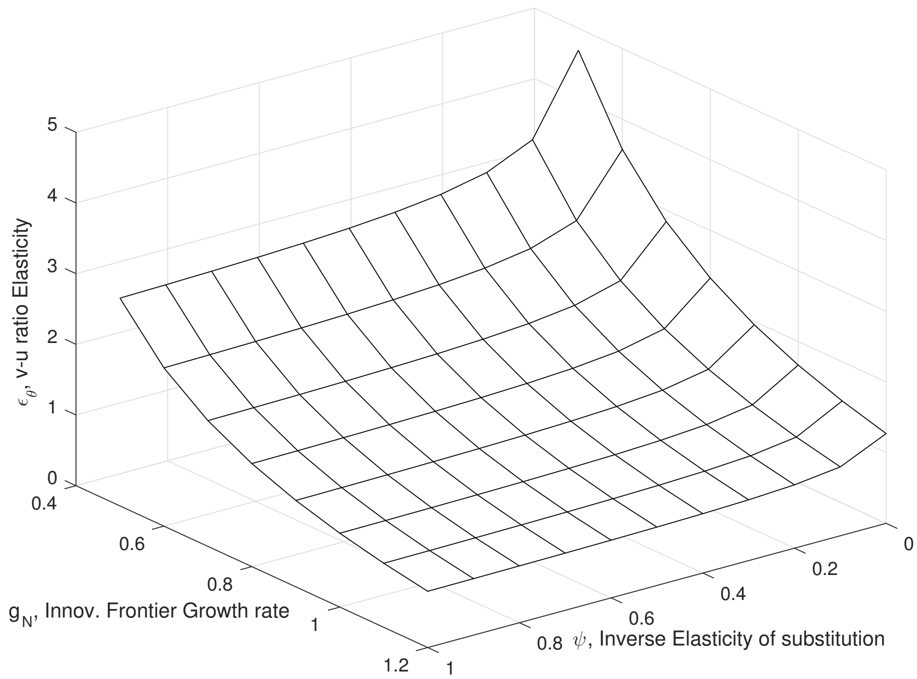
where from (30) and (31) the finding rate can be expressed as follows $f(\overline{\theta}) = \overline{\theta}q(\overline{\theta})$. and the elasticity $\varepsilon_{f,\theta}$ is given by $1 + q'(\overline{\theta})/q(\overline{\theta})^2 f(\overline{\theta})$. Thus $\varepsilon_{f,\theta}$ denotes the elasticity of $f(\overline{\theta})$ with respect to v–u ratio.

When $\overline{g}_N = 1$ (exogenous productivity process) and $\alpha = 0$ (capital share), our model becomes identical to the Shimer setup.[9] In particular Shimer notes that only when the worker has no bargaining power, that is $\xi = 0$, the elasticity of v–u ratio with respect to the net productivity substantially increases, and however it is still too small to match the data (puzzle of Shimer). On the contrary, in our model, given $\psi > 0$ and $\overline{g}_N \neq 0$, the calibration of these deep parameters constitutes a possible channel that can help to attenuate the Shimer puzzle. The surface of Figure 4 illustrates the sensitivity of the elasticity $\varepsilon_{\theta,p}$ to different values of ψ and g_N.

There is a large literature that documents and examines the high–frequency fluctuations of the labor market in response of shocks. For instance, a first group of papers,

[9] See Shimer (2005, p. 36).

Figure 4: Sensitivity of the elasticity $\varepsilon_{\theta,p}$ to ψ and g_N



Abraham and Katz (1986), argue that the downward-sloping Beveridge curve is inconsistent with models in which unemployment is driven by fluctuations in the separation rate. That leads them to advocate an alternative in which unemployment fluctuations are driven by productivity shocks. On the other hand, Pries (2004) and Gomes et al. (2001) among others rather assume that employment fluctuations are largely due to time-variation in the separation rate, minimizing the role played by the observed cyclicality of the v–u ratio. den Haan et al. (2000) show that fluctuations in the separation rate amplify productivity shocks in a model similar to the one examined here; however, they do not discuss the cyclical behavior of the v-u ratio. Shimer (2005) argues that a search and matching model in which wages are determined by Nash bargaining cannot generate substantial movements along a downward-sloping Beveridge curve in response to shocks of a plausible magnitude. A labor productivity shock results primarily in higher wages, with little effect on the v-u ratio. A separation shock generates an increase in both unemployment and vacancies. Thus Shimer (2005) as well as other recent work inspired by its paper overemphasize the need for wage rigidity to account for the observed business-cycle-frequency fluctuations in unemployment and job vacancies in response to shocks of a plausible magnitude.[10] Unlike all these papers that have focused on high–frequency fluctuations of the labor market, the novelty in our paper is that we seek to account for both the high– and medium–frequency

[10]See e.g. Hall (2005a), Gertler and Trigari (2009), Gertler and Trigari (2009) among others. Moreover, other reconfigurations have also been suggested involving inter alia: upfront cost for firms to secure credit (Wasmer, 2004); high value of leisure for workers (Hagedorn and Manovskii, 2008); cost of delay for firms that participate in alternating-offer bargaining (Hall and Milgrom, 2008); government mandated unemployment compensation and layoff costs (Ljungqvist and Sargent, 2015) or diminishing marginal revenue product of labor (Dao and Delacroix, 2017).

labor market dynamics. More precisely, in this paper, we argue that the medium-term fluctuations in the labor market may be explained by the same endogenous variables as in Hall (2005b), Shimer (2004) among others. However our model does not permit for sticky wages. Instead, we assume that movements in productivity are endogenous, which are primarily caused by R&D activities. Specifically, this paper analytically shows that firms do not react to exogenous technology shocks as in the standard search model, but they rather react to changes of new technologies by adjusting employment, which leads to endogenous movements in both productivity and labor market tightness.

5. Concluding remarks

The paper develops a tractable dynamic general equilibrium model to investigate how new technologies affect the medium-term fluctuations in unemployment and job vacancies. We also use the model to address the Shimer puzzle. This paper makes some progress in understanding of the technological change for both the high– and medium–frequency labor market dynamics. By incorporating expanding input varieties and labor market frictions in a standard real business cycle model, we have shown that interaction the augmented model can solve a part of Shimer puzzle in the medium-term. Our model does not embed wage rigidity, nor is it based on a small surplus calibration.

In this paper we focus on a single type of technology and not address issues related to the direction and bias of technical change. As argued by Acemoglu (1998) and others, technological change is not neutral. It benefits some agents in the economy more than others for many problems in macroeconomics. Hence, limiting the analysis to only one type of technological change is not entirely satisfactory. This potentially obscures the different competing effects that determine the nature of technological progress. Thus one natural extension would be to examine how the direction and bias of new technologies can affect the labor market dynamics in the medium–term business.

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