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Capital, Endogenous Separations, and the Business Cycle

by Björn van Roye and Dennis Wesselbaum

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JEL classification: E22, E32, J64.

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Capital, Endogenous Separations, and the Business Cycle*

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Abstract

This paper implements capital in an endogenous separations New Keynesian matching model. We propose a more general approach, such that workers have unrestricted access to a proportional share of the capital stock. We find that the introduction of capital generates an important channel for the transmission of aggregate productivity shocks. Our model generates higher volatilities of key variables and enhances the performance of the matching model to generate stylized facts in response to an aggregate productivity shock. However, we show that this holds only in the presence of sticky prices and that our additional channel seems to be important for the propagation of productivity shocks.

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1 Introduction

The ability of search and matching models to replicate stylized facts has been assessed by various authors. Shimer (2005) in his seminal contribution finds that the standard search and matching model with exogenous separations within a RBC partial equilibrium context is not able to replicate the fluctuations of key labor market variables. A promising solution approach was introduced by Hall (2005) implementing a real wage rigidity, increasing the surpluses of the firm over the cycle and increasing the response of vacancies. However, it appears that real wage rigidity on the one hand is not able to significantly improve the model's performance, as shown by Krause and Lubik (2007). Additionally, there is evidence that the wage of new entrants is not rigid as shown by Haefke et al. (2009). A different solution proposed by Hagedorn and Manovskii (2008) sets the value of leisure close to the wage and the worker's bargaining power close to zero. Therefore, firms relative profits are heavily affected from productivity changes, hence increasing the volatility. However, their approach shows an unrealistic high sensitivity of the unemployment rate with respect to unemployment benefit changes. It appears that a satisfying solution has not been found yet.

As proposed by Hornstein et al. (2005), the introduction of capital might be an important feature that has been rather neglected in the search and matching RBC and NKM literature. Capital, and to be more precisely the cost of investment, add an additional variable to the firm's decision problem. Fluctuations along this margin should also have an impact on the labor market decisions of the firm, creating a capital-labor trade-off for the firm. In contrast to the recent literature, we do not assume that there is heterogeneity in matches, since we allow unrestricted access to capital and technology to all matches at any time. Therefore, we deviate from the vintage capital literature.[1] The vintage approach is based upon the seminal contribution from Caballero and Hammour (1991), assuming that due to the process of innovation jobs that contain the newest technologies are created, whereas outdated jobs are destructed. Along this line, Michelacci and Lopez-Salido (2007) and Costain and Reiter (2008) introduce the vintage theory to matching models in a RBC context with exogenous separations. Our approach has to be understood as a more general case of modelling capital and consistently as a starting point in the process of understanding the relevance of capital in matching models. Furthermore, we address the question how capital is allocated within a firm.

[1] See e.g. Boucekkine et al. (2006), Eyigungor (2006) or Hornstein et al. (2007).

In the following, we build a New Keynesian DSGE model with search frictions, capital and purely endogenous separations. Although their is no consensus in the literature on the proper determination of the separation margin, following Fujita and Ramey (2007, 2008) and Ramey (2008) empirical evidence seems to favor endogenous separations. Balleer (2009) shows that the separation rate increases after a positive technology shock and that the standard model generates the volatility of these variables conditional on technology shocks. In addition, Barnichon (2009) finds that around business cycle turning points the separation rate is causative for most of unemployment movements.
Firms rent any desired quantity of capital on a frictionless capital market as in Pissarides (2000). We evaluate the performance along the labor market dimension. For this purpose, and to have a transparent judgement basis for later purpose, we scrutinize U.S. data and perform a statistical analysis.[2] Our findings are presented in Table 1.

- Table 1 about here -

The main findings can be summarized as follows

- **Unemployment and Vacancies**
  Unemployment is almost 9 times as volatile as productivity, while vacancies are even 10 times as volatile. Labor market tightness is even 19 times as large as labor productivity, while the correlation between unemployment and vacancies is strongly negative.

- **Job Finding Rate**
  The job finding rate is about twice as volatile as labor productivity, strongly autocorrelated and pro-cyclical.

- **Job Creation and Destruction Rates**
  The job creation and destruction rates are negatively correlated (-0.36) and show much smaller standard deviations than unemployment or vacancies.[3]

We show that the introduction of capital adds an important channel for the transmission of aggregate productivity shocks. We create the empirical values of standard deviations for unemployment and vacancies in response to

[2] To be consistent with the findings from Shimer (2005), we apply his methodology.

[3] Values for the job creation and destruction rates are based on Krause and Lubik (2007), using HP filtered data from 1964:Q1 to 2002:Q3.

an aggregate productivity shock. Moreover, we show that this results only holds, if we also introduce sticky prices. In the RBC version of our model, the performance gain is much smaller compared with the sticky price versions. In addition, we find that our additional worker-specific capital channel seems to be important in order to replicate stylized facts.

The remainder is organized as follows. In the next section we derive the model for later analysis. In section 3 we calibrate and close the model while section 4 discusses and compares models with and without capital. Section 5 provides a robustness analysis and section 6 concludes.

2 A Matching Model with Capital

In this section, we present a New Keynesian model with endogenous separations, search frictions and capital. Households maximize consumption by choosing the optimal consumption path of a CES aggregate of differentiated products and make the investment decision. Firms, acting on a monopolistically competitive market, maximize profits by setting prices - time-dependent pricing following Rotemberg (1982) - and choosing the optimal levels of employment and capital subject to price adjustment costs, hiring costs and capital adjustment costs. Separations are driven by job-specific productivity shocks affecting new and old jobs generating a flow of worker. In addition, the monetary authority targets the nominal interest rate by a standard Taylor-rule.

2.1 Consumer Preferences

We assume a discrete-time economy with an infinite living representative household who makes its investment decision and seeks to maximize its utility given by

$$U = E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\sigma} - 1}{1-\sigma} \right], \tag{1}$$

where E is the expectation operator, $C_t = \left[\int_0^1 C_{it}^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}$ is the Dixit-Stiglitz aggregator, β is the discount factor, and the degree of risk aversion is given by σ. We assume that a household consists of a continuum of members, inelastically suppling one unit of labor and being represented by the unit interval.

In addition, and following Merz (1995), Andolfatto (1996), and Poilly and

Sahuc (2008), we assume consumption pooling. The household maximizes consumption subject to the intertemporal budget constraint

$$C_t + I_t + \frac{B_t}{P_t} = R_{t-1}\frac{B_{t-1}}{P_t} + \mathcal{W}_t + bu_t + T_t + \Pi_t + r_t^K K_t, \tag{2}$$

where b is the value of home production, such that bu_t accordingly is the income of unemployed household members. $\mathcal{W}_t$ is labor income, B_t is bond holding which pays a gross interest rate R_t. Π_t are aggregate profits and T_t are real lump sum transfers from the government. The household owns the capital stock and rents it to the firm, such that earnings from providing capital are given by $r_t^K K_t$, where r_t^K is the rental rate. It is derived from the corresponding cost minimization problem of the firm. The capital stock accumulates according to

$$K_{t+1} = (1-\delta)K_t + \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right) I_t, \tag{3}$$

where δ is the depreciation rate, I_t corresponds to investment and $S\left(\frac{I_t}{I_{t-1}}\right)$ is a function which describes investment adjustment costs as in Christiano et al. (2005).[4] The first-order condition with respect to investment is given by

$$1 = Q_t\Phi_t\left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}}\right] + \beta E_t\left[\Lambda_{t+1}Q_{t+1}\Phi_{t+1}S'\left(\frac{I_t}{I_{t-1}}\right)\left(\frac{I_{t+1}}{I_t}^2\right)\right], \tag{4}$$

where Tobin's Q is the ratio of the Lagrangian multipliers attached to equations (2) and (3), i.e.

$$Q_t = \beta E_t\left[\Lambda_{t+1}r_{t+1}^k + Q_{t+1}(1-\delta)\right], \tag{5}$$

where $\Lambda_{t+1} = \beta\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma}$ is the stochastic discount factor. By minimizing total expenditures, we obtain the demand function $C_{it} = \left(\frac{P_{it}}{P_t}\right)^{-\epsilon} C_t$ and by solving the households maximization problem, we obtain the standard Euler equation for intertemporal consumption flows, i.e.

$$C_t^{-\sigma} = \beta R_t E_t\left[\frac{P_t}{P_{t+1}}C_{t+1}^{-\sigma}\right]. \tag{6}$$

[4]In steady state, $S(\cdot)$ satisfies $S = 0, S' = 0$ and $S'' > 0$.

2.2 Entry and Exit Site

The firm searches for workers on a discrete and closed market. Trade in the labor market is uncoordinated, costly and time-consuming. Therefore, labor market frictions are modelled via a Cobb-Douglas type matching function with constant returns to scale, i.e.[5]

$$\Psi(u_t, v_t) = m(u_t)^{\mu}(v_t)^{1-\mu}. \tag{7}$$

The function gives the number of new employment relationships at the beginning of the next period. Where u_t is the number of unemployed worker and v_t is the number of open vacancies, assumed to lie on the unit interval $v_t = \int_0^1 v_{it} di$. Where $\mu \in (0, 1)$ is the elasticity of the matching function with respect to unemployment and the matching efficiency is governed by $m > 0$. The matching function is homogenous of degree one, strictly increasing in each of its arguments, strictly concave and twice continuously differentiable. The homogeneity assumption leads to the probability of a vacancy being filled in the next period $q(\theta_t) = m\theta_t^{-\mu}$, where $\theta_t = v_t/u_t$ corresponds to labor market tightness.
The firm's exit site is determined by endogenous separations only. Therefore, the total number of separations at firm i is given by $\rho_{it} = F(\tilde{a}_t)$, where $\tilde{a}_{it}$ is an endogenously determined critical threshold. If the specific productivity of a job is below this threshold, it is not profitable and separation takes place. $F(a)$ is a time-invariant distribution with positive support $f(a)$. Connecting the results for job creation and the job destruction enables us to determine the evolution of employment at firm i as

$$n_{it+1} = (1 - \rho_{it+1})(n_{it} + v_{it}q(\theta_t)). \tag{8}$$

The firm adjusts employment by posting vacancies and by setting the critical threshold, which then influences the separation rate.

2.3 Firm's Maximization

If the matching process has been successful, production commences along the production function given by

$$y_{it} = A_t K_{it}^{\alpha} \left[n_{it} \int_{\tilde{a}_{it}} a \frac{f(a)}{1 - F(\tilde{a}_{it})} da \right]^{1-\alpha} = A_t K_{it}^{\alpha} \left[n_{it} H(\tilde{a}_{it}) \right]^{1-\alpha}, \tag{9}$$

[5]In their empirical analysis Petrongolo and Pissarides (2001) find that the Cobb-Douglas function with constant returns to scale is the most appropriate specification.

where $\alpha < 1$, aggregate productivity A_t is common to all firms, the specific productivity a_{it} is idiosyncratic and every period it is drawn in advance of the production process from the corresponding distribution function. The worker specific production function can then be written as

$$y_{jt} = A_t k_{ijt}^{\alpha} \tilde{a}_{jt}^{1-\alpha}, \tag{10}$$

where worker j's share of the overall capital in firm i is $k_{ijt} = K_{it}/n_{it}$. Since we assume homogeneity in matches, every worker has a proportional access to the capital stock.

The firm chooses the optimal path of $\{n_{it}, v_{it}, P_{it}\}_{t=0}^{\infty}$ and hence solves the following maximization problem

$$\Pi_{i0} = E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[\frac{P_{it}}{P_t} y_{it} - \mathcal{W}_{it} - c v_{it} - r_t^K K_t - \frac{\psi}{2} \left(\frac{P_{it}}{P_{it-1}} - \pi \right)^2 Y_t \right], \tag{11}$$

being real revenue depleted by total costs.[6] Due to the introduction of nominal and real frictions, total costs are also determined by vacancy posting costs ($c > 0$), capital rental costs and price adjustment costs ($\psi \geq 0$).

The wage bill is given by the aggregate of individual wages

$$\mathcal{W}_{it} = n_{it} \int_{\tilde{a}_{it}} w_t(a) \frac{f(a)}{1 - F(\tilde{a}_{it})} da. \tag{12}$$

Combining the derivatives with respect to employment and vacancies, one can show that the job creation condition is given by

$$\frac{c}{q(\theta_t)} = E_t \beta_{t+1} (1 - \rho_{t+1}) \left[(1-\alpha) \varphi_{t+1} A_{t+1} K_{t+1}^{\alpha} n_{t+1}^{-\alpha} H(\tilde{a}_{t+1})^{1-\alpha} - \frac{\partial \mathcal{W}_{t+1}}{\partial n_{t+1}} + \frac{c}{q(\theta_{t+1})} \right], \tag{13}$$

where $\beta_{t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t}$ is the stochastic discount factor. This condition reflects the hiring decision as a trade-off between the costs of a vacancy and the expected return. Where $1/q(\theta_t)$ is the duration of the relationship between firm and worker.

A key distinctiveness of New Keynesian models is their capability to elucidate the reciprocity of output and inflation. In these models inflation dynamics are defined by the New Keynesian Phillips curve (NKPC).[7]

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \kappa \hat{\varphi}_t, \tag{14}$$

[6] Perfect capital markets imply that the firm discounts with the households subjective discount factor.

[7] For simplicity, we illustrate the log-linearized version of the New Keynesian Phillips Curve.

where $\kappa = (\epsilon - 1)/\psi$ and $\hat{\varphi}_t$ reflects real marginal costs.
Subsequently, we will shed light on the wage setting process to derive an expression for the individual real wage which will allow us to study the firm's separation decision more precisely and further determine the critical threshold.

2.4 Wage Setting

A successful match shares an economic rent which is splitted according to individual Nash bargaining. The firm-worker pair then solves the following problem

$$w_t = \underset{w_t}{\operatorname{argmax}} \left\{ (W_t - U_t)^{\eta} (J_t - V_t)^{1-\eta} \right\}, \tag{15}$$

where the first term is the worker's surplus, the latter term is the firm's surplus and $0 \leq \eta \leq 1$ is the exogenously determined, constant relative bargaining power. It can be shown that the individual real wage satisfies the optimality condition

$$W_t(a_t) - U_t = \frac{\eta}{1-\eta} J_t(a_t). \tag{16}$$

To obtain an explicit expression for the individual real wage, we determine the asset value functions and substitute them into the Nash bargaining solution (16).
For the firm the asset value of the job depends on the real revenue, the real wage and if the job is not destroyed, the discounted future value. Otherwise, the job is destroyed and hence has zero value. In terms of a Bellman equation the asset value is given by:[8]

$$J_t(a_t) = \varphi_t A_t k_t^{\alpha} a_t^{1-\alpha} - w_t(a_t) + E_t \beta_{t+1} \left((1-\rho_{t+1}) \int_{\tilde{a}_{t+1}} J_{t+1}(a) \frac{f(a)}{1 - F(\tilde{a}_{t+1})} da \right). \tag{17}$$

The asset value of being employed for the worker consists of the real wage, the discounted continuation value and in case of separation the value of being unemployed

$$\begin{aligned} W_t(a_t) &= w_t(a_t) + E_t \beta_{t+1} (1-\rho_{t+1}) \int_{\tilde{a}_{t+1}} W_{t+1}(a) \frac{f(a)}{1 - F(\tilde{a}_{t+1})} da \\ &+ E_t \beta_{t+1} \rho_{t+1} U_{t+1}. \end{aligned} \tag{18}$$

[8] Notice, that we drop subscripts i due to symmetry.

Analogously, the asset value of a job seeker is given by

$$\begin{aligned} U_t &= b + E_t\beta_{t+1}\theta_t q(\theta_t)(1-\rho_{t+1})\int_{\tilde{a}_{t+1}} W_{t+1}\frac{f(a)}{1-F(\tilde{a}_{t+1})}da \qquad (19) \\ &+ E_t\beta_{t+1}(1-\theta_t q(\theta_t)(1-\rho_{t+1}))U_{t+1}. \end{aligned}$$

Unemployed worker receive the value of home production b, the discounted continuation value of being unemployed and if she is matched she receives the value of future employment. Inserting these value functions into the Nash bargaining solution yields the individual real wage

$$w_t(a_t) = \eta(\varphi_t A_t k_t^{\alpha} a_t^{1-\alpha} + c\theta_t) + (1-\eta)b. \qquad (20)$$

The firm will endogenously separate from a worker, if and only if

$$J_t(a_t) < 0, \qquad (21)$$

i.e. if the worker's asset value is smaller than zero.
After some algebra, the threshold is given by

$$\tilde{a}_t = \left\{ \frac{1}{(1-\eta)\varphi_t A_t k_t^{\alpha}} \left[(1-\eta)b + \eta c\theta_t - \frac{c}{q(\theta_t)} \right] \right\}^{\frac{1}{1-\alpha}}. \qquad (22)$$

In the next section, we close our model by calibrating deep parameters and by defining monetary policy.

3 Model Solution

3.1 Closing the Model

The monetary authority targets the short-term nominal interest rate by following a standard Taylor rule, given by

$$\left(\frac{R_t}{\bar{R}}\right) = \left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{Y_t}{\bar{Y}}\right)^{\phi_y} \qquad (23)$$

where ϕ_π and ϕ_y are the respective weights imposed by the monetary authority. The aggregate productivity shock is formulated as

$$A_t = A_{t-1}^{\rho_A} e^{\alpha_{A,t}}. \qquad (24)$$

The i.i.d. error term is $\alpha_{A,t} \sim N(0, \sigma_A)$ with $cov(A_{t-1}, \alpha_{A,t}) = 0 \; \forall \; t$.
The resource constraint is given by

$$Y_t = C_t + I_t - cv_t. \tag{25}$$

Then the model is linearized around its deterministic steady state and simulated with the software package Dynare.
For the given stochastic process $\{A_t\}_{t=0}^{\infty}$ and the interest rate $\{r_t\}_{t=0}^{\infty}$ a determined equilibrium is a sequence of allocations and prices $\left\{\tilde{a}_t, C_t, I_t, jcr_t, jdr_t, K_t, m_t, n_t, \pi_t, \varphi_t, Q_t, \rho_t, r_t^K, \theta_t, u_t, v_t, w_t, y_t\right\}_{t=0}^{\infty}$, which for given initial conditions, satisfies equations (3), (4), (5), (6), (7), (8), (9), (13), (14), (20), (22), (23), (24), (25), the definitions for labor market tightness, job destruction and creation rate, the interest rate shock, the law of motion for unemployment, the separation rate, and the firm's cost minimization solution.

3.2 Calibration

We calibrate the model on a quarterly basis for the United States and set parameter values according to stylized facts and the relevant literature. We set the Taylor Rule parameters to standard values of 1.5 with respect to inflation (ϕ_π) and to 0.125 to output (ϕ_y). The discount factor is set to 0.98 percent which results into a steady state interest rate of approximately 2 percent. For the risk aversion parameter σ we choose to set the parameter to a value of 2. Following Krause and Lubik (2007), we set the price adjustment cost ψ to a value of 105. With regard to the labor market variables, we choose a steady-state employment rate of 0.88 which results in an equilibrium unemployment rate of 12 percent analogously to Krause and Lubik (2007). The separation rate is set to 0.10 according to Hall (2005) which is due to endogenous separations only. The distribution parameters μ and σ_{ln} of the log-normal distribution are chosen to match the observed volatility of job destruction. We set the parameters to 0 resp. 0.12. The job filling rate is assumed to equal 0.7 which corresponds to a monthly rate of 0.3 which is consistent with U.S. data[9], whereas the probability for a worker of finding a job, $\theta q(\theta)$ is equal to 0.6, which represents an unemployment average duration of 1.7 as in Cole and Rogerson (1999). In order to ensure a socially efficient outcome, we respect the Hosios (1990) rule, viz. the elasticity of matches with respect to unemployment μ is set equal to the

[9] See Blanchard and Gali (2007).

workers bargaining power $\eta = 0.5$. Missing parameter values are computed from the steady state. The coefficient with respect to the capital share is set to the standard value of 1/3, inducing a labor share of roughly 60 percent. According to Smets and Wouters (2007), we set the second derivative of the investment adjustment cost function $S(\cdot)$ to 0.8. In line with Christiano et al. (2005) the depreciation rate is $\delta = 0.025$. The value of the autocorrelation of the aggregate productivity shock is set to 0.66, to balance the estimation results from Prescott (1986) and Altig et al. (2005). Prescott (1986) finds a value of 0.95, while Altig et al. (2005) find a value of 0.1 for a shock to capital embodied technology and 0.87 for a neutral technology shock. For the interest rate shock, we calibrate the persistence parameter to 0.49.

4 Model Comparison

In this section, we start by analyzing differences between a standard search and matching model with endogenous separations (baseline model, henceforth) and a model which additionally includes capital as developed above. Then, we evaluate the differences between the RBC core and the model with sticky prices. Finally, we quantify the importance of the worker-specific capital channel.

4.1 The Importance of Capital

Figure 1 shows the impulse responses to a positive aggregate productivity shock for the baseline model and the model with capital and the worker-specific capital channel.

- Figure 1 about here -

In the baseline model, GDP increases persistently due to the rise of aggregate productivity, which boosts production. Simultaneously, marginal costs decrease and consistently, - via the NKPC - inflation decreases. The monetary authority lowers its interest rates, since it puts more weight on inflation than on output. The expansionary behaviour of the central bank acts as a supplementary increase in aggregate demand such that firms increase their labor demand.[10] As a consequence, the separation threshold decreases and firms aim to keep more workers in order to remedy increased

[10] If inflation would not react on impact, employment would fall, because the firm would be capable of satisfying the unchanged demand with less workers.

demand. Analogously, job creation rises on impact, turns negative in the consecutive quarter, however.[11] As characteristic for endogenous separation models, we identify a separation driven adjustment mechanism. In contrast to the baseline model, and as a consequence of the capital-labor trade-off, unemployment increases in the capital model, because firms substitute labor by capital. The increase of unemployment in response to a technology shock has been shown by Gali (1999) and Balleer (2009). While in the baseline model the productivity of workers increases because aggregate productivity increases, the capital model suggests an additional channel, working along the per-worker capital stock, i.e. k_{ijt}. The direct effect works through the increase in the capital stock, viz. an increased capital stock makes workers more productive. The indirect effect is a consequence of the substitution of labor. Since employment decreases, the capital share of worker i clearly increases, additionally increasing her productivity. This, in turn, also rises the incentive to separate from less productive workers.

Furthermore, the dynamic response of vacancies changes significantly in the model with capital. While in the baseline model vacancy postings drop on impact and converge from below to the steady state, in the capital model vacancies initially increase and converge from above. As before, the capital-labor trade-off causes this changed vacancy posting behavior. Consider the vacancy posting condition (13). Due to the increase in the capital stock and aggregate productivity, the expected profit from a vacancy increases. This is further enhanced by the same mechanism that we already identified. Because firms decrease employment, the per-worker capital stock significantly increases such that there is "capital left" for new workers, i.e. the expected profit from a posted vacancy is large, since the worker's productivity will be large due to (i) the large aggregate productivity and (ii) due to the large worker's capital share (especially, in relation to the steady state).

Our findings are mirrored in the second moments of our simulation (see Table 2 and Table 3).

- Table 2 about here -

- Table 3 about here -

With respect to our empirical analysis in the introduction, we show that the model with capital performes outstandingly. In particular, the standard

[11] This follows straightforward from the job creation condition. Initially, expected profits rise - since productivity increases - but then hiring costs increase, driving the system back to the equilibrium.

deviations of vacancies and unemployment are in line with the evidence, such that there is no Shimer-puzzle. However, the volatility of labor market tightness is four times below the target value. In addition, except from the standard deviation of separations, all values are close to their empirical pendants. We admit that the challenge of the endogenous separation model, the separation driven adjustment mechanism, is still present in the capital model and causes the relatively bad performance of second moments. For instance, the fact that there is no Beveridge curve and the second moments with respect to the separation rate are not in line with empirical observations. In addition, in the capital model - and in contrast to the baseline model - the standard deviations of the job creation and destruction rates are too high compared to empirical estimates and there correlation is close to (plus) one (being around 0.5 in the baseline model). However, we find that the capital model produces higher persistence values. Unfortunately, this persistence is not endogenous in the sense that a one-off shock creates almost no persistence. Therefore, the model only generates higher persistence to an autocorrelated shock.

4.2 Do Sticky Prices Matter?

In the previous section we have concluded that the introduction of capital improves the performance of the endogenous separation matching model along the labor market dimension and in terms of autocorrelations. With capital, the model is able to replicate the stylized facts reasonably well, the only exception being the missing Beveridge curve. Now, we want to address the question, whether our results are driven by the introduction of sticky prices. Therefore, we use the partial equilibrium - flexible price - core of our model (see Appendix C), use the same calibration and simulate this model. Our results are presented in Table 4 and Figure 2.

- Table 4 about here -

- Figure 2 about here -

We find that the core model creates too less volatile of almost every variable. However, the standard deviation of the separation rate fits the empirical value quite well. Introducing capital leads the model to generate more volatility, even if the RBC capital version does not improve the performance of the model by a significant number. We can draw the conclusion that the interaction of sticky prices and adjustment costs - labor and capital adjustment costs - is causative for the performance of our model in the previous

section. Sticky prices imply that the adjustment process of consumption and output is more persistent over the cycle, such that the firm has less incentives to separate from workers and increases its demand for capital. Coherently, this has an impact on the labor market, implying larger reactions of key variables and therefore creating more volatility. Furthermore, the introduction of real rigidities and its interaction with sticky prices, makes real marginal costs less sensitive to exogenous disturbances which also drives the results via the interest rate channel.
We have to conclude that the introduction of capital itself does improve the model but only the interaction of sticky prices and capital - and to be more precise, the real rigidities going along with this feature - lead the model to replicate the stylized facts reasonably well.

4.3 The Worker-Specific Capital Channel

In what follows, we want to quantify the importance of the additional capital channel that works along the worker-specific capital stock k_{ijt}. Our results are presented in Table 5.

- Table 5 about here -

If we compare the results based on this specification, we can conclude that this additional channel significantly changes the results. Ignoring this channel leads the model to produce too much volatility with respect to vacancies (almost twice as volatile as data suggests). This also holds for the job finding rate and the separation rate. However, the standard deviation from the labor market tightness is much more in line with empirical evidence than in the model that features this channel. The model without the additional capital channel performes worse in terms of replicating correlations than the full model. Now, why is this additional channel changing the results? The reason is, that due to this additional channel workers become more profitable in response to a positive technology shock. There are, in fact, three channels, (i) aggregate productivity increases, (ii) the overall capital stock, K_t, increases and (iii) employment decreases, in turn increasing the per-worker capital share. Hence, the firm has less incentives to separate from workers and, simultaneously, to post new vacancies compared to the model with this channel.
We can draw the conclusion, that the worker-specific capital channel matters for the dynamics of the model. The allocation of capital to workers should not be overseen in the design of models that feature capital. Our assumption of proportional capital, although being rather simple, seems to

perform quite well, but has to be considered as a startingpoint in tackling this problem.

5 Robustness Issues

In what follows, we perform a robustness analysis of our results for the capital model and the productivity shock only. Setting the value of the autocorrelation of the shock to 0.89 (the empirical autocorrelation) significantly increases the fluctuations of all variables. However, our qualitative results remain unaffected and the nature of the shock allows us to choose a smaller value of the shock than normally employed in RBC models. Increasing the unemployment rate (0.3 in this example) leaves our quantitative results unaffected while it significantly decreases the volatility of aggregate fluctuations (e.g. std(v)=0.08). In particular, the standard deviations of the job creation and destruction rate are significantly reduced. Along this line, decreasing the unemployment rate (5 % in this example) increases the fluctuations of labor market variables. Since this is a well-known effect of matching models, we continue with the discussion of the steady state separation rate. Setting this value to 0.15 as in Andolfatto (1996) leaves our results almost unaffected. A value of $\psi = 40$ increases the volatility of key variables such as unemployment or vacancies.
The value of capital adjustment costs plays a major role for the dynamics of the capital model. Increasing this value (doubled, in this example) increases the standard deviations of labor market variables, because adjustments along the capital margin are more expensive. In addition, we simulated the model with a money growth rule (results are available upon request) and find the same internal propagation mechanism for the volatility of labor market variables as described in the precedent section.[12] While we observe a significant improvement in the second moments of the model, the dynamic saddle path is almost identical to the model without capital.

6 Conclusion

In this paper we have shown that the introduction of capital adds an important channel for the propagation of productivity shocks. For this purpose, we develop a New Keynesian model with search frictions, purely endogenous separations and capital. In deviating from the vintage capital theory,

[12]Our simulation shows no Shimer puzzle.

we consider a more general case of capital in DSGE models. In our model, workers have an unrestricted and proportional access to the firm's capital stock, i.e. we do not assume heterogeneity in matches. Therefore, we explicitly introduce the problem of capital allocation within firms. Within this framework we show that the dynamic adjustment path of the capital model deviates significantly from the baseline model to an aggregate productivity shock. The reason for the differences between these two models is the fact that the firm substitutes labor by capital. In addition, the main channel causing the discussed differenes is the worker's capital share being affected (i) directly, by the increase of the capital stock, and (ii) indirectly, by the decrease of employment. The capital model is able to fit the empirical values reasonably well, while other shocks may play an important role as well, which is left to the future. We admit that the underlying challenge of endogenous separation models - the separation driven adjustment mechanism - is not resolved, such that the second moments are still not entirely in line with the evidence.

With our more general approach of implementing capital, and by proposing an additional transmission channel, we justify to further consider the role of capital, capital adjustment costs and the capital-labor trade-off in matching models.

While the introduction of capital significantly improves the model, this only holds, if we also introduce sticky prices. Only the interaction between these two features, together with the matching framework is able to replicate the stylized facts. Furthermore, our additional capital channel proves to be important for the propagation of productivity shocks. It acts as an accelerator in increasing the worker's productivity and therefore changing incentives to hire and fire. We leave further investigations of the allocation of capital to workers to future research.

We can draw the final conclusion, that capital should not be overseen in the design of matching models and in tackling persistent problems of those models.

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B Set of Non-Linear Equations for the Capital Model with Worker-Specific Capital

1. Separations

$$\rho_t = \rho^x + (1-\rho^x)F(\tilde{a}_t), \tag{26}$$

2. Labor Market Tightness

$$\theta_t = \frac{v_t}{u_t}, \tag{27}$$

3. Matches

$$\Psi_t = m u_t^{\mu} v_t^{1-\mu}, \tag{28}$$

4. Job Finding Rate

$$jfr_t = m\theta_t^{1-\xi}, \tag{29}$$

5. Employment Evolution

$$n_{t+1} = (1-\rho_{t+1})(n_t + v_t q(\theta_t)), \tag{30}$$

6. Job Creation Condition

$$\frac{c}{q(\theta_t)} = \beta_{t+1}(1-\rho_{t+1})\left[(1-\alpha)\varphi_{t+1}A_{t+1}K_{t+1}^{\alpha}n_{t+1}^{-\alpha}H(\tilde{a}_{t+1})^{1-\alpha} - \frac{\partial W_{t+1}}{\partial n_{t+1}} + \frac{c}{q(\theta_{t+1})}\right], \tag{31}$$

7. Threshold

$$\tilde{a}_t = \left\{\frac{1}{(1-\eta)\varphi_t A_t k_t^{\alpha}}\left[(1-\eta)b + \eta c\theta_t - \frac{c}{q(\theta_t)}\right]\right\}^{\frac{1}{1-\alpha}}, \tag{32}$$

8. Wage

$$w_t = \eta(\varphi_t A_t k_t^{\alpha}\tilde{a}_t^{1-\alpha} + c\theta_t) + (1-\eta)b, \tag{33}$$

9. Identity Unemployment

$$u_t = 1 - n_t, \tag{34}$$

10. Job Destruction Rate

$$jdr_t = \rho_t - \rho^x, \tag{35}$$

11. Job Creation Rate

$$jcr_t = \frac{(1-\rho_t)v_{t-1}q(\theta_{t-1})}{n_{t-1}} - \rho^x, \tag{36}$$

12. Euler Equation

$$C_t^{-\sigma} = \beta R_t \frac{1}{\pi_{t+1}} C_{t+1}^{-\sigma}, \tag{37}$$

13. Output

$$y_t = A_t K_t^{\alpha} \left[n_t H(\tilde{a}_{t+1})\right]^{1-\alpha}, \tag{38}$$

14. Capital

$$K_{t+1} = (1-\delta)K_t + \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right) I_t, \tag{39}$$

15. Investition

$$1 = Q_t \Phi_t \left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}}\right] + \beta\left[\Lambda_{t+1} Q_{t+1} \Phi_{t+1} S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_{t+1}^2}{I_t}\right], \tag{40}$$

16. Tobins Q

$$Q_t = \beta\left[\Lambda_{t+1} r_{t+1}^k + Q_{t+1}(1-\delta)\right], \tag{41}$$

17. Rental Rate

$$\frac{K_t}{n_t H(\tilde{a}_t)} = \frac{\alpha}{1-\alpha}\frac{w_t}{r_t^k}, \tag{42}$$

18. Taylor Rule

$$\frac{r_t}{r} = \left(\frac{\pi_t}{\pi}\right)^{\phi_\pi}\left(\frac{y_t}{y}\right)^{\phi_y} \varrho_t, \tag{43}$$

19. Phillips Curve (log-linearized)

$$\hat{\varphi}_t = \frac{\psi}{\upsilon - 1}\hat{\pi}_t - \beta\frac{\psi}{\upsilon - 1}\hat{\pi}_{t+1}, \tag{44}$$

20. Identity

$$y_t = C_t + I_t + cv_t, \tag{45}$$

21. Technology Shock (log-linear)

$$A_t = \rho_A A_{t-1} + \epsilon_{A,t}, \tag{46}$$

C Set of Non-Linear Equations for the RBC Core with Worker-Specific Capital

1. Separations

$$\rho_t = \rho^x + (1-\rho^x)F(\tilde{a}_t), \tag{47}$$

2. Labor Market Tightness

$$\theta_t = \frac{v_t}{u_t}, \tag{48}$$

3. Matches

$$\Psi_t = m u_t^{\mu} v_t^{1-\mu}, \tag{49}$$

4. Job Finding Rate

$$jfr_t = m\theta_t^{1-\xi}, \tag{50}$$

5. Employment Evolution

$$n_{t+1} = (1-\rho_{t+1})(n_t + v_t q(\theta_t)), \tag{51}$$

6. Job Creation Condition

$$\frac{c}{q(\theta_t)} = \beta_{t+1}(1-\rho_{t+1})\left[(1-\alpha)\varphi_{t+1}A_{t+1}K_{t+1}^{\alpha}n_{t+1}^{-\alpha}H(\tilde{a}_{t+1})^{1-\alpha} - \frac{\partial W_{t+1}}{\partial n_{t+1}} + \frac{c}{q(\theta_{t+1})}\right], \tag{52}$$

7. Threshold

$$\tilde{a}_t = \left\{\frac{1}{(1-\eta)\varphi_t A_t k_t^{\alpha}}\left[(1-\eta)b + \eta c\theta_t - \frac{c}{q(\theta_t)}\right]\right\}^{\frac{1}{1-\alpha}}, \tag{53}$$

8. Wage

$$w_t = \eta(\varphi_t A_t k_t^{\alpha}\tilde{a}_t^{1-\alpha} + c\theta_t) + (1-\eta)b, \tag{54}$$

9. Identity Unemployment

$$u_t = 1 - n_t, \tag{55}$$

10. Job Destruction Rate

$$jdr_t = \rho_t - \rho^x, \tag{56}$$

11. Job Creation Rate

$$jcr_t = \frac{(1-\rho_t)v_{t-1}q(\theta_{t-1})}{n_{t-1}} - \rho^x, \tag{57}$$

12. Euler Equation (log-linear)

$$\hat{\lambda}_t = \hat{\lambda}_{t+1} + \hat{r}_t^k, \tag{58}$$

13. Output

$$y_t = A_t K_t^{\alpha} \left[n_t H(\tilde{a}_{t+1}) \right]^{1-\alpha}, \tag{59}$$

14. Capital

$$K_{t+1} = (1-\delta)K_t + \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right) I_{t,} \tag{60}$$

15. Investition

$$1 = Q_t \Phi_t \left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}} \right] + \beta \left[\Lambda_{t+1} Q_{t+1} \Phi_{t+1} S'\left(\frac{I_t}{I_{t-1}}\right) \frac{I_{t+1}^2}{I_t} \right], \tag{61}$$

16. Tobins Q (log-linear)

$$\hat{Q}_t = \beta(1-\delta)\hat{Q}_{t+1} + (1-\beta(1-\delta))\hat{r}_{t+1}^k - \hat{r}_t^k, \tag{62}$$

17. Rental Rate

$$\frac{K_t}{n_t H(\tilde{a}_t)} = \frac{\alpha}{1-\alpha} \frac{w_t}{r_t^k}, \tag{63}$$

18. Identity

$$y_t = C_t + I_t + cv_t, \tag{64}$$

19. Technology Shock (log-linear)

$$A_t = \rho_A A_{t-1} + \epsilon_{A,t}, \tag{65}$$

20. Marginal Utility (log-linear)

$$\hat{\lambda}_t = -\hat{C}_t. \tag{66}$$

D Tables and Figures

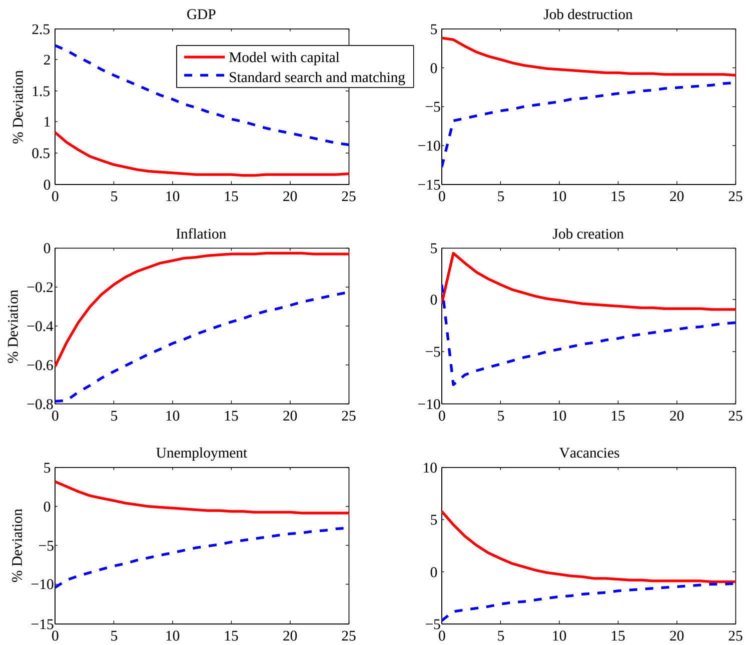

Figure 1: Impulse Responses to a 1 % Productivity Shock. Model without capital vs. model with capital and worker-specific capital channel.

Table 1: Business Cycle Properties of the U.S. Economy.

		u	v	θ	jfr	ρ	p
Standard Deviation		0.18	0.20	0.37	0.03	0.01	0.02
Autocorrelation		0.97	0.97	0.97	0.92	0.81	0.89
Correlation Matrix	u	1	-0.89	-0.97	-0.95	0.68	-0.38
	v	-	1	0.98	0.85	-0.70	0.40
	θ	-	-	1	0.92	-0.71	0.40
	jfr	-	-	-	1	-0.55	0.41
	ρ	-	-	-	-	1	-0.50
	p	-	-	-	-	-	1

Notes: We use quarterly, seasonally adjusted, HP filtered ($\lambda = 10^5$) data from 1955:Q1 to 2009:Q2 provided by the OECD and the BLS. All variables respond to log deviations.

Table 2: Business Cycle Properties of the Matching Models - Sticky Price Version.

		u	v	θ	jfr	ρ	p
Standard Deviation							
Capital Model		0.21	0.21	0.02	0.01	0.22	0.01
Baseline Model		0.07	0.05	0.02	0.01	0.07	0.01
Autocorrelation							
Capital Model		0.92	0.89	0.70	0.70	0.89	0.66
Baseline Model		0.64	0.62	0.68	0.68	0.42	0.66
	u	1	0.99	-0.15	-0.15	0.99	0.37
Correlation	v	-	1	-0.05	-0.05	0.99	0.47
Matrix	θ	-	-	1	1	-0.09	0.84
Capital	jfr	-	-	-	1	-0.09	0.84
Model	ρ	-	-	-	-	1	0.42
	p	-	-	-	-	-	1
	u	1	0.99	-0.99	-0.99	0.97	0.99
Correlation	v	-	1	-0.99	-0.99	0.97	0.99
Matrix	θ	-	-	1	1	-0.95	-0.99
Baseline	jfr	-	-	-	1	-0.96	-0.99
Model	ρ	-	-	-	-	1	0.96
	p	-	-	-	-	-	1

Notes: Theoretical Moments.

Table 3: Business Cycle Properties of the Matching Models - Sticky Price Versions.

	y	π	u	v	θ	jfr	ρ
Standard Deviation							
U.S. economy	**1.00**	**1.11**	**6.90**	**8.27**	**14.96**	**3.24**	**3.73**
Capital Model	1.00	0.74	12.59	14.94	2.42	0.98	14.48
Baseline Model	1.00	0.41	4.25	1.75	2.50	1.02	3.66
Autocorrelation							
U.S. economy	**0.87**	**0.56**	**0.97**	**0.97**	**0.97**	**0.92**	**0.81**
Capital Model	0.70	0.55	0.58	0.57	0.51	0.51	0.51
Baseline Model	0.86	0.86	0.84	0.81	0.86	0.86	0.63
	y	0.39	0.36	-0.16	-0.26	-0.33	0.36
	π	1	-0.23	0.10	0.17	0.004	0.006
Correlation	u	-	1	-0.89	-0.97	-0.95	0.68
Matrix	v	-	-	1	0.98	0.85	-0.70
U.S	θ		-	-	1	0.92	-0.71
data	jfr		-	-	-	1	-0.55
	ρ		-	-	-	-	1
	y	-0.89	0.65	0.67	0.80	0.80	0.65
	π	1	-0.92	-0.93	-0.98	-0.98	-0.92
Correlation	u		1	0.99	0.97	0.97	0.99
Matrix	v	-	-	1	0.97	0.97	0.99
Capital	θ	-	-	-	1	1.00	0.97
model	jfr	-	-	-	-	1	0.97
	ρ	-	-	-	-	-	1
	y	-0.99	-0.99	-0.99	1.00	1.00	-0.95
	π	1	0.99	0.99	-1.00	-1.00	0.95
Correlation	u	-	1	0.99	-0.99	-0.99	0.96
Matrix	v	-	-	1	-0.99	-0.99	0.97
Baseline	θ	-	-	-	1	1.00	-0.95
model	jfr	-	-	-	-	1	-0.95
	ρ	-	-	-	-	-	1

Notes: Statistics for the U.S. economy are computed using quarterly HP-filtered data from 1964:1 to 2002:3. Statistics for the model economies are computed by simulating the model 100 times for 200 periods. The statistics are averages over the HP-filtered simulations. The standard deviations of all variables are relative to output.

Table 4: Business Cycle Properties of the Matching Models - RBC Versions.

		u	v	θ	jfr	ρ	p
Standard Deviation							
RBC Capital Model		0.03	0.03	0.009	0.004	0.15	0.01
RBC Baseline Model		0.02	0.01	0.001	0.002	0.02	0.02
Autocorrelation							
RBC Capital Model		0.60	0.60	0.59	0.59	0.66	0.66
RBC Baseline Model		0.63	0.60	0.67	0.67	0.38	0.66
	u	1	0.99	0.99	0.99	0.99	0.99
Correlation	v	-	1	0.99	0.99	0.99	0.99
Matrix	θ	-	-	1	1	0.45	0.99
RBC Capital	jfr	-	-	-	1	0.45	0.98
Model	ρ	-	-	-	-	1	0.36
	p	-	-	-	-	-	1
	u	1	0.99	-0.99	-0.99	0.96	0.99
Correlation	v	-	1	-0.99	-0.99	0.97	0.99
Matrix	θ	-	-	1	1	-0.95	-0.99
RBC Baseline	jfr	-	-	-	1	-0.95	-0.99
Model	ρ	-	-	-	-	1	0.95
	p	-	-	-	-	-	1

Notes: Theoretical Moments.

Table 5: Sticky Price Capital Model without Worker-Specific Capital Channel.

		u	v	θ	jfr	ρ	p
Standard Deviation		0.20	0.44	0.26	0.10	0.31	0.01
Autocorrelation		0.69	0.83	0.92	0.92	0.80	0.66
	u	1	0.95	0.84	0.84	0.98	0.68
	v	-	1	0.97	0.97	0.99	0.42
Correlation Matrix	θ	-	-	1	1	0.93	0.19
	jfr	-	-	-	1	0.93	0.19
	ρ	-	-	-	-	1	0.53
	p	-	-	-	-	-	1

Notes: Theoretical Moments.

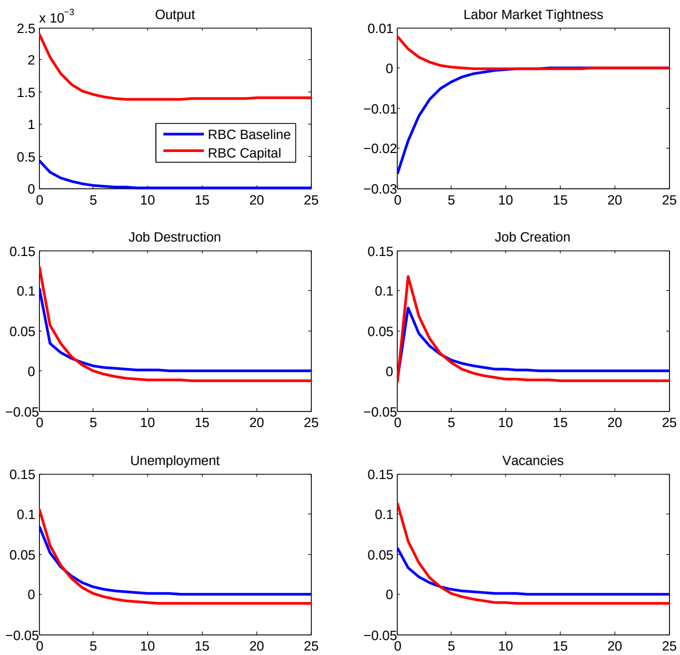

Figure 2: Impulse Responses to a 1 % Productivity Shock. RBC Versions. Model without capital vs. model with capital and worker-specific capital channel.