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Evaluating the empirical performance of DSGE models: What is the role of search and matching frictions in the labor and capital markets?

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EVALUATING THE EMPIRICAL PERFORMANCE OF DSGE MODELS:

WHAT IS THE ROLE OF SEARCH AND MATCHING FRICTIONS IN THE LABOR AND CAPITAL MARKETS?

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Evaluating the empirical performance of DSGE models: What is the role of search and matching frictions in the labor and capital markets?

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Abstract

A major perspective in explaining involuntary unemployment is to recognize the existence of job market frictions, in particular, job market matching frictions. The workhorse model employed is the Diamond- Mortensen-Pissarides (DMP) model. Similar to the labor market, the market for physical capital markets exhibits the same characteristics with a pool of unsold inventory as well as used capital that is sold and reallocated to other firms. Nevertheless, past research has highlighted several issues of the DMP model in matching the characteristics of the labor market. In a model enriched with labor participation flows and job separation, I evaluate the model performance in resolving the issues in the Krause and Lubik (2007) model in the presence of nominal price rigidity. The model resolves the failure in generating the Beveridge curve in the presence of endogenous job destruction. Separately, in a RBC model with frictional labor and physical capital market and endogenous labor participation, I evaluate the model prediction in a context where labor disutility is procyclical under both contemporaneous shocks and news shocks.

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I dedicate this to my wife, Agnes.

Chapter 1

Endogenous job separation and labor participation rate

1.1 Abstract

In this paper, I worked with a New Keynesian model that features endogenous job separations, labor force participation and worker turn-over costs. The modeling of endogenous separations that is based on a reservation productivity acting on a continuous match productivity distribution is in the tradition of denHaan (2000) and Walsh (2005). The modeling of endogenous labor participation is in the spirit of Gali (2011). Yet, these models have inherent performance issues. The objective of this research is to evaluate the performance of a model that incorporates the coexistence of these labor flows that have often been ignored in macro-economic models and at the same accounting for the costs of hiring and job separations. Labor turnover costs have been well documented in empirical literature (see Sakellaris (2000)). However, most models have chosen to focus only on search costs and to a lesser extent, separation costs while ignoring training and adaptation costs. The model that is developed here incorporates these details and is evaluated on its ability to match the moments of the US economy, in the context of the issues highlighted in Krause and Lubik (2007) for the basic endogenous separation model. The basic endogenous separation model shows a) a positive correlation between unemployment and vacancies, b) a positive correlation between job creation rate and job destruction rate, c) a high volatility in the job creation rate and d) a negative correlation between output and inflation

rate. These characteristics are counter-factual to the empirical behavior of the US economy.

In a model featuring both endogenous labor participation rate and nominal wage rigidity through staggered wage negotiaton in the Calvo spirit, Gali (2011) is able to demonstrate results that are in line with the cyclical properties of unemployment and labor force participation and employment volatility. This was achieved however with the calibration of labor bargaining share that is outside the range of empirical evidence.

A novel approach in the model developed in this chapter relates to the detailing of worker replacement costs. The incorporation of the different components of worker turnover costs by including training and adaptation costs, in addition to search costs and job separation costs, adds a new dimension to the model that has not been explored in the literature.

The model in this paper shows several improvements in performance achieving the negative correlation between unemployment and vacancies, between job creation rate and job destruction and reducing the high volatility in the job creation rate. The behavior of labor force participation rate is also relatively in line with the empirical data. The issue of the negative correlation between inflation and output remains unresolved and arises from the model's behavior to technology shocks.

1.2 Introduction

In recent literature, researchers modeling the labor market typically employed DSGE models that are augmented with match frictions in the mode of the Diamond. Mortensen and Pissarides model, that feature labor flows between employment and unemployment but with the assumption of a constant exogenous separation rate. The assumption of a constant separation rate is motivated by research findings that concluded that variations in the job creation rate is the dominant contributing factor to unemployment in postwar US data. Shimer (2005) found, by comparing the unemployment series derived from a constant job separation rate, using calculations following the methodology of Pissarides (1996), with the actual unemployment series of postwar US, that there is no significant difference between the two series. On the other hand, when a constant job finding is imposed, the computed series is significantly different from the actual unemployment series.

Hall (2005) arrives at the same conclusion by comparing the volatiliy rates of the inflow and outflow rates for unemployment that the US unemployment is driven mainly by variations in the job finding rate. Since then, a constant separation rate is often assumed in DSGE models. However, Pissarides (2007) argued that despite the lower volatility of the separation rate, the correlation between the inflow and outflow rate is significant. Furthermore, in subsequent research findings, the respective contributions of the inflow and outflow rate are estimated to be at 30:70 in researches by Elsby, Michaels and Solon (2007), Braun, De Bock and DeCecio (2006) as well as Mortensen and Nagypal (2007).

As reported in Gali (2011), conditional on monetary and demand shocks, the participation rate has a correlation of 0.2 with output although the correlation with output is acyclical (0.02) conditional on technology shocks. The latter together with the low volatility results in its movement being ignored in most models. This is however disputed in recent papers on labor participation. Nucci and Riggi (2014) and Campolmi and Gnocchi (2014) highlighted that the effect of labor participation cannot be ignored in the study of monetary policies. The endogenous flow of labor in and out of labor force has also become a focus in current research partly because of its behavior in the latest recession. Erceg and Levin (2013), Christiano et al (2014) are examples. Making labor participation endogenous however, introduces additional difficulty to the model because wealth effect and reduced job separation rate affects the incentive for unemployed workers to search for a job in countervailing directions.

This paper integrates endogenous labor participation rate into a model of endogenous labor separation in the tradition of denHaan et al (2000), Krause and Lubik (2007) and Walsh et al (2005). The model has been extended by Zanetti (2011) to evaluate the effects of labor institutions endogenous separations. The extended form with unemployment insurance is used in Albertini and Fairise (2013) and Ahrens, Nejati and Pfeiffer (2014). I choose to use a variant of the model in using productivity dependent firing taxes in the spirit of Wesselbaum (2007). In this paper, I extended the model with endogenous labor participation along the line of Gali (2011) and investigated the performance of the model with endogenous labor participation in coexistence with endogenous separations and its fit with empirical data using calibrations from the literature in real wage rigidity and firing taxes. As demonstrated by Gali (2011) and Blanchard and Gali (2010), wage rigidity is needed in their model to create volatility in their model. In particular the Gali

(2011) model employs nominal wage rigidity that arises from staggered bargaining in the spirit of Calvo staggered pricing while Blanchard and Gali (2011) used real wage rigidity induced from a wage norm. I chose the latter approach as a simplifying approach so as to focus on the other aspects of the model instead of the details of the wage negotiation mechanisms. The same approach is also used in Albertini and Fairise (2013).

One particular aspect of this paper is to highlight the adaptation and training costs involved in a labor match formation. Matching costs in the form of fixed sunk in cost have been demonstrated in two papers by Silva and Toledo (2009) and (2011) and discussed in Pissarides (2009) and Nagypal and Mortensen (2009) as one mechanism in the partial resolution of the volatility puzzle highlighted in Shimer (2005). Empirical studies by Sakellaris (2000) and Barron et al (1999) on adjustment costs highlight that substantial training and adaptation costs are incurred in the first quarter of a newly hired worker. In labor matching models, these costs, in addition to direct search costs, affect the volatility of the matching rate.

1.3 Literature

This section summarizes the cyclical properties of employment, labor force, unemployment, vacancies and job creation and destruction rate from the literature and the performance related issue highlighted in the endogenous separation model. A summary of the postwar US labor market statistics is provided in Table 1 as reported from Krause and Lubik (2007) augmented with labor force participation rate from Gali (2011).

As highlighted in Krause and Lubik (2007), there are several issues in the performance of the basic endogenous separation model related to the models used in denHaan (2000), Walsh (2005) and Trigari (2007). The issues are a) positive correlation between unemployment rate and vacancies b) positive correlation between job creation and job destruction c) negative correlation between output and inflation d) high job creation rate and job destruction rate volatilities. The incorporation of a fully rigid wage rate in the model is shown to be able to address only the issue of the Beveridge curve while accentuating the negative correlation between output and inflation.

TABLE 1.1: Unconditional Moments for US Economy 1964- 2002

Standard Deviations	
Output	(1.62)
Inflation	1.11
Real Wage	0.69
Unemployment	6.9
Vacancy	8.27
Tightness	14.96
Job Creation Rate	2.55
Job Destruction Rate	3.73
Labor Participation	0.3
Correlations	
U,V	-0.96
JCR, JDR	-0.36
Labor Force, Y	0.2
Y,Inflation	0.39

* The standard deviations for all variables except output is relative to the standard deviations for output.

However researchers, who are involved in the study of labor institutions and unemployment insurance programs, have to address the issue of endogenous separation of labor. To confront the issues highlighted by Krause and Lubik (2007), they have to make extensions to the endogenous separation model to match the empirical behavior of the labor market. Some of the works that have attempted to address the issues in extensions of the basic Krause and Lubik model are Wesselbaum (2007), Ahrens, Nejati and Pfeiffer (2014), Albertini and Fairise (2013) and Zanetti (2011) with varying degrees of success. The last applies to UK data where the characteristics of the idiosyncratic match productivities are different from the US. Wesselbaum (2007) extended the model with productivity dependent firing cost while maintaining flexible wages and found that the Beveridge curve could not be obtained under any reasonable firing tax calibrations. Albertini and Fairise (2013) and Ahrens, Nejati and Pfeiffer (2014) made extensions that involved a firing tax scheme that sponsors the unemployment insurance and studied the design and impact of the firing schemes. Albertini and Fairise (2013)'s version is a RBC model and also features real wage rigidity while Ahrens, Nejati and Pfeiffer (2014) worked with only monetary shocks. The last paper attempts to account for the empirical results using the experience rating scheme behind the firing tax and unemployment insurance program in the US. The formulation involves a firing tax scheme that increases with the duration of unemployment which essentially is dependent on the job finding rate.

1.4 Model

The base model used in my work is an extension of the model in Krause and Lubik (2007), and Zanetti (2011). The model is a New Keynesian model featuring price stickiness, labor matching frictions and endogenous separations. I extend the model with endogenous labor participation modified from from Gali (2011). Additionally, while Krause and Lubik (2007) uses a Rotemberg pricing friction in a single sector, I followed Walsh (2005) and Zanetti (2011) in applying the modeling approach of separating the pricing frictions and labor frictions into a two sector production economy. The additioanl elements in the model are a)the inclusion of labor training and adaptation costs in the formation of labor matches and b) external habit formation and monetary policy inertia. In the following subsections, I describe a) the representative household, b) the intermediate goods sector with the labor market frictions, c) the final good sector with nominal pricing frictions and d) the monetary authority.

1.4.1 Representative Household

Each household is characterized by a continuum of members belonging to a unit interval. Following Merz (1996), I assume that there is complete consumption insurance within the representative household. Each member of the household consume the same amount regardless of his employment status and income. The household then maximizes a discrete time lifetime utility function as follows:

$$E_0 \sum_{t=0}^{\infty} \beta^t U\big(C_t, N_t, U_t^o\big) \tag{1.1}$$

subject to a period budgetary constraint of

$$P_t C_t + Q_t B_t \leq B_{t-1} + (1-\delta_t) N_{t-1} P_t \bar{W}_t + M_t P_t W_t^n - T_t + Profits_t \tag{1.2}$$

where β is the time discount factor and $0 < \beta < 1$. C_t is the quantity consumed of an index of the different types of final goods produced by the monopolistic retailers(j) on the unit interval such that

$$C_t = \left\{ \int_0^1 C_t(j)^{1-\frac{1}{\gamma}} dj \right\}^{\frac{\gamma}{\gamma-1}}$$

where γ is the elasticity of substitution between the final goods. Each period, the household allocates the income from various sources to consumption and savings in bonds, B_t purchased at the price of Q_t.

As in Walsh (2005), Gali (2011) and numerous research work in the literature, I have chosen to abstract away the accumulation of capital to focus on the labor market mechanisms. The first source of income is $(1-\delta_t)N_{t-1}P_t\bar{W}_t$ which is the real wage earned by $(1-\delta_t)N_{t-1}$ members of the household who are employed in the last period and are not separated this period. N_t represents the number of household members employed for the period, t and its transition is described in equation (1.9). δ_t is the total separation rate in the period and $\bar{W}_t$ is the average wage rate for the period. New job matches, M_t, earn W_t^n in the period. A second source of income is the profits in the form of dividends from the firms that the household owns fully. The government imposes a lump sum tax/transfer T_t. The redemption of last period's bond constitutes the final source of income.

The household members incur disutility from participating in the labor market which consists of disutility from working $\nu_n(N_t)$ and as well as from search, $\nu_u(U_t^o)$. The disutility functions are define as follows:

$$\nu_n(N_t) = \frac{\chi_n N_t^{1+\phi_n}}{1+\phi_n}$$

$$\nu_u(U_t^o) = \frac{\chi_u (U_t^o)^{1+\phi_u}}{1+\phi_u}$$

In the above utility functions, N_t and U_t^o denote respectively the fraction of household members engaged in employment and the fraction allocated to participate in the search market at the beginning of the period. Non-participation incurs zero disutility. The total labor force participation F_t is given by

$$F_t = U_t + N_t \tag{1.3}$$

In equation (1.3), U_t represents the end of period unemployment.

The household's per period utility function is assumed to take the following form with external habit formation:

$$U(C_t, N_t, U_t^o) = \log\left(C_t - hC_{t-1}^A\right) - \nu_n(N_t) - \nu_u(U_t^o) \tag{1.4}$$

In equation (2.6), the external habit stock is C_{t-1}^A. I defined it to be equivalent to last period's aggregate consumption, C_{t-1} (in level only) and the household's optimal decision does not involve the decision with regards to the habit stock. h is the index of habit formation.

1.4.2 Production Sector

The production sector consists of two sectors, a monopolistic final good retail sector and a perfect competition intermediate goods sector. The final goods producers purchase intermediates, "differentiate" the goods and sell the final goods to the households at differentiated pricing. Pricing frictions is localized in the final goods retail sector. The perfect competition intermediate goods sector takes the price of intermediates as given and produces a homogeneous intermediate good with labor as the input. As all intermediate good firms are symmetric, I use a representative firm. The modeling strategy of the two sector production is along the line of work by Walsh (2005) so that we can separate the analysis of the labor market frictions from the pricing frictions by localizing the pricing frictions in the final goods retail sector and the labor market frictions in the intermediate goods production sector. I first describe the intermediate goods sector and the labor market frictions.

Intermediate Goods Sector The intermediate goods sector consists of competitive firms taking price, P_t^i as given. Each firm owns a continuum of job matches. Each job match (indexed by i) consists of one worker and is characterized by an idiosyncratic match productivity, $Z_t(i)$. The firm draws the idiosyncratic productivities for its job matches every period which corresponds to one quarter. This follows the standard approach used in Krause and Lubik (2007), denHaan (2000) and Walsh (2005). Empirically, this is in line with the evidence on the persistence of match idiosyncratic productivity shocks (see Fujita and Ramey (2012)). The match productivity, $Z_t(i)$ is i.i.d. and is drawn from a constant distribution

G(Z). The job matches are also affected by an aggregate technology shock A_t, which affects all matches equally and follows an autoregressive process:

$$\log(A_t) = \rho_a \log(A_{t-1}) + e_{a,t} \tag{1.5}$$

where $e_{a,t}$ is i.i.d. normal across periods. The output function of a job match is then $A_t Z_t(i)$. Because each job is characterized by Z_t, we drop the index i and identify the job match by its match productivity Z_t.

1.4.2.1 Hiring and Job Separations

As in Gali (2011), hiring takes place at the beginning of the period. With contemporaneous hiring, the model takes into account transitions from unemployment into employment within the period which one period ahead hiring models cannot account for. Search models typically increase the unemployment pool to include marginally attached workers to account for flows from non-participation into employment - see Krause and Lubik(2007) as an example).

As is standard in DMP matching models, hiring is subject to a matching function in the form of a Cobb Douglas production function with vacancy postings, V_t and U_t^o, the unemployed members of the households who are allocated to the search market at the beginning of the period, as inputs so that the matching function is characterized by both a constant return to scale and and concavity to each input. The matching function used is as follows:

$$M_t = m\,(U_t^o)^{\mu}\,(V_t^o)^{1-\mu} \tag{1.6}$$

In the above equation, m denotes the efficiency of the matching function and μ denotes the elasticity of hiring to unemployment and $0 < \mu < 1$. The matching function then gives the following identities. When the market tightness is θ_t which is defined as $\frac{V_t}{U_t^o}$ the firm faces a worker finding probability, $q(\theta_t)$ while the worker faces a job finding probability of $f(\theta_t)$. The identities are as follows:

$$q(\theta_t) = m\,(\theta_t)^{-\mu} \tag{1.7a}$$

$$f(\theta_t) = m\,(\theta_t)^{1-\mu} \tag{1.7b}$$

Additionally, the relationship between the end of period unemployed workers, U_t and beginning of period unemployed workers U_t^o is given as follows:

$$U_t^o = \frac{1}{1 - f(\theta_t)} U_t \tag{1.8}$$

In our model, hiring and job separations take place after both aggregate productivity and match productivities are observed. Job separations comprise of two forms, an exogenous separation rate of δ and an endogenous separation rate determined by the reservation idiosyncratic productivity, $\underline{Z}_t$. As in Zanetti (2011) which follows Thomas (2008) and Mortensen and Pisarrides (2000), newly formed job matches are not subject to separation in the first period of their formation. All job matches from the last period i.e. $t-1$ which draws a match productivity below the reservation productivity, $\underline{Z}_t$ are destroyed prior to production and therefore the endogenous separation rate of these job matches is given by $\delta_{x,t} = G(\underline{Z}_t)$. It follows that the transition for employment N_t is as follows:

$$N_t = (1 - \delta)(1 - G(\underline{Z}_t))N_{t-1} + q(\theta_t)V_t \tag{1.9}$$

1.4.2.2 Intermediate Firm's Optimal Behavior

The production function of the representative firm is determined by the number of job matches from the last period that are not separated given the idiosyncratic productivities drawn in the current period, the aggregate productivity shock A_t and the new matches formed in the period with the starting productivity, Z_t^n. This is given by

$$X_t = A_t N_{t-1}(1 - \delta)(1 - G(\underline{Z}_t))\bar{Z}_t + A_t q(\theta_t) V_t Z_t^n \tag{1.10}$$

In equation (1.10), X_t is the output of the representative firm. $\bar{Z}_t$ is the average productivity of the job matches conditional on the idiosyncratic productivity being above the cut off productivity, $\underline{Z}_t$ i.e. jobs that have survived into production. It is given by:

$$\bar{Z}_t = \frac{\int_{\underline{Z}_t}^{\infty} Z dG(Z)}{1 - G(\underline{Z}_t)}$$

The last term in equation (1.10) defines the contribution from the new matches with starting productivity Z_t^n

The firm's optimization problem for each period consists of choosing the reservation productivity $\underline{Z}_t$ and vacancy postings, V_t in order to hire the necessary workers, N_t to maximize the present discounted value of the real profit stream. The firm takes as given the price of the intermediate good, P_t^I and the labor market tightness, θ_t. The expected present discounted value of the real profit stream is given by

$$E_t \sum_{k=0}^{\infty} \Lambda_{t+k|t} \{ \frac{P^i_{t+k}}{P_{t+k}} X_{t+k} - N_{t+k-1}(1-\delta)(1-G(\underline{Z}_{t+k}))\bar{W}_{t+k} - \\ W^n_{t+k} q(\theta_{t+k}) V_{t+k} - HC_{t+k} - N_{t+k-1}(1-\delta)(1-G(\underline{Z}_{t+k}))\Phi(\underline{Z}_{t+k}) \} \tag{1.11}$$

In equation (1.11), the firm optimizes the expected profit stream which is discounted by the stochastic discount factor, $\Lambda_{t+k|t} = \beta^k U'(C_{t+k})/U'(C_t)$. The first three items within the parenthesis are respectively the real revenue and total real wage paid to the workers which consist of both the "old" unseparated workers and new hires. The hiring cost, HC_{t+k} for the period is incurred by posting V_t vacancies at a vacancy posting cost of c per vacancy posting and a training and adaptation cost for each new hire such that it is given as follows:

$$HC_t = cV_t + q(\theta_t)V_t H_n A_t \frac{P^i_t}{P_t} Z^n_t \tag{1.12}$$

where H_n is the proportion of revenue lost for the new matches. The average real wages paid to the workers is given by the average real wage rate paid to surviving job matches:

$$\bar{W}_t = \frac{\int_{\underline{Z}_t}^{\infty} W_t(Z)dG(Z)}{1-G(\underline{Z}_t)} \tag{1.13}$$

The last term consists of a firing cost. The firing cost for the destruction of a job match is TZ_t. It follows that $\Phi(\underline{Z}_t)$ is a function of the reservation productivity and is given by:

$$\Phi(\underline{Z}_t) = \frac{T\int_0^{\underline{Z}_t} ZdG(Z)}{1-G(\underline{Z}_t)} \tag{1.14}$$

This formulation of firing cost which is dependent on productivity of the separated matches follows the formulation from Wesselbaum (2009) as opposed to Zanetti (2011)'s formulation of fixed firing cost. As put forward in Wesselbaum(2009), the firing cost presented as such is increasing in match productivity. As opposed to a constant firing cost, this is more realistic and is a simple representation of wage dependent firing cost. Take for example Campolmi and Faia (2011) which includes a wage based firing cost and Ahrens, Nejati and Pfeiffer (2014) which analyses unemployment insurance that is financed through a firing cost with dependencies on the wage rate and an expected unemployment duration. In that paper, they also included a benchmark model with a productivity dependent firing cost of a version of Zanetti (2011).

The opimization of equation (1.11) is subject to the employment transition equation (1.9). With ξ_t as the Lagrangian multiplier on equation (1.9) and using the identities (1.10) and (1.13), the first order conditions with respect to N_t and V_t are as follows:

$$\xi_t = E_t \left[\Lambda_{t+1|t}(1-\delta)(1-G(\underline{Z}_{t+1}))\{\frac{P^i_{t+1}}{P_{t+1}} A_{t+1}\bar{Z}_{t+1} - \bar{W}_{t+1} - \Phi(\underline{Z}_{t+1}) + \xi_{t+1}\} \right] \tag{1.15}$$

$$\frac{c}{q(\theta_t)} + H_n \frac{P^i_t}{P_t} A_t Z^n_t = \frac{P^i_t}{P_t} A_t Z^n_t - W^n_t + \xi_t \tag{1.16}$$

Equation (1.16) is the break even condition for a hiring such that the cost of a hiring is equated to the expected marginal value of a new worker which consists of the first period return of a job match minus the wage and the expected discounted value of the job match in the second period subjected to job destruction and the expected separation cost should the job be destroyed using the definition of ξ_t in Equation (1.15).

The first order condition in selecting the reservation idiosyncratic productivity $\underline{Z}_t$ results in the following equation:

$$\frac{P^i_t}{P_t} A_t \underline{Z}_t - W_t(\underline{Z}_t) + \xi_t = -T\underline{Z}_t \tag{1.17}$$

In equation (1.17), the value of the job to be destroyed is negative because of firing costs. As long as the job value is greater than the cost of layoff, it will be kept. Taking into consideration the job creation equations (1.16) and (1.15), the job destruction condition can be expressed as:

$$\frac{P^i_t}{P_t} A_t\{Z^n_t - \underline{Z}_t\} - W^n_t + W_t(\underline{Z}_t) - T\underline{Z}_t = \frac{c}{q(\theta_t)} + H_n \frac{P^i_t}{P_t} A_t Z^n_t \tag{1.18}$$

1.4.3 Household Intertemporal Savings

The representative household optimizes equation (2.1) with the budget constraint of (2.2). The intertemporal optimality condition with respect to consumption and bonds savings are as follows:

$$Q_t = E_t \beta \frac{C_t - C_{t-1}^A}{C_{t+1} - C_t^A} \frac{P_t}{P_{t+1}} \tag{1.19}$$

The real stochastic discount at time t that is applied on the future revenue at time t+k, $\Lambda_{t+k|t}$ is given by $\beta^k \frac{C_t - hC_{t-1}^A}{C_{t+k} - hC_{t+k-1}^A}$. Equivalently, the price of bond is related to the nominal interest rate, i_t, which the monetary authority targets as a policy tool is given by:

$$Q_t = \frac{1}{1 + i_t} \tag{1.20}$$

1.4.4 Labor Force Participation

The value of non-participation of a household member to the household is normalized to 0 with no disutility incurred. For an interior solution, the household is indifferent between sending the marginal member to participate in the job search and not sending him. The value of a newly matched worker to the household is defined as follows:

$$V_t^n = W_t^n - \chi_n N_t^{\phi_n} / U'(C_t) + E_t \Lambda_{t+1|t} (1 - \delta)(1 - G(\underline{Z}_{t+1})) V_{t+1}^e \tag{1.21}$$

In equation (1.21), V_t^e is the average value of a marginal employed worker to the household who has been working for more than one period and is given by

$$V_t^e = \bar{W}_t - \chi_n N_t^{\phi_n} / U'(C_t) + E_t \Lambda_{t+1|t} (1 - \delta)(1 - G(\underline{Z}_{t+1})) V_{t+1}^e \tag{1.22}$$

In the above equations, the new (existing average) worker obtains a wage W_t^n ($\bar{W}_t$) while working and the household incurs a disutility of $\chi_n N_t^{\phi_n} / U'(C_t)$ for each marginal worker, expressed in consumption good. The job match is subject to both endogenous and exogenous destruction in the beginning of the next period and this is reflected in the future expected average value.

When a member of household is searching in the labor market, the houseold incurs a marginal disutility of $\chi_u (U_t^o)^{\phi_u}$ and gets compensated with the probability of getting matched successfully to a job. The job search process takes place at the beginning of the period and the successful job match is rewarded with V_t^n. The optimality condition with respect to U_t^o for the interior condition is given by:

$$\chi_u (U_t^o)^{\phi_u} / U'(C_t) = f(\theta_t) V_t^n \tag{1.23}$$

1.4.5 Wage Setting

I consider the flexible wage scheme first. The wage setting follows a typical Nash bargain set up that is often used in the literature. The value of a matched job of idiosyncratic productivity Z_t to a firm is given by:

$$\begin{aligned} J(Z_t) =& \frac{P_t^i}{P_t} A_t Z_t - W(Z_t) + \\ & E_t \left[\Lambda_{t+1|t} (1-\delta) \{ \int_{\underline{Z}_{t+1}}^{\infty} J(Z) dG(Z) - (1 - G(\underline{Z}_{t+1})) \Phi(\underline{Z}_{t+1}) \} \right] \end{aligned} \tag{1.24}$$

The value of a vacancy, V_t^{firm}, is driven to 0 with free entry such that V_t^{firm} does not feature in the firm's match surplus.

At the reservation productivity, $J(\underline{Z}_t) = -T\underline{Z}_t$. It is easy to check that equation (1.24) is consistent with (1.17). $V^e(Z_t)$, the value of a job match of productivity Z_t to the household is given by:

$$V^e(Z_t) = W(Z_t) - \chi_n N_t^{\phi_n} / U'(C_t) + E_t \Lambda_{t+1|t} (1-\delta)(1 - G(\underline{Z}_{t+1})) V_{t+1}^e \tag{1.25}$$

Under a flexible Nash bargaining scheme, workers and the representative firm bargain over the match surplus by maximizing the Nash product of the surpluses such that:

$$W_t^f(Z_t) = \underset{W(Z_t)}{\text{argmax}} (J(Z_t) + TZ_t)^{1-\eta} V^e(Z_t)^{\eta} \tag{1.26}$$

In equation (1.26), the threat point for the firm is $-TZ_t$ and I use η as a parameter for the worker's bargaining strength. As in the above, we respected the Bonding critique that part of the firing cost can be passed from the firm to the worker in the wage bargaining process. The wage for a job with idiosyncratic shock of Z_t is then given by:

$$W_t^f(Z_t) = \eta \{ \frac{P_t^i}{P_t} A_t Z_t + TZ_t - E_t \Lambda_{t+1|t} (1-\delta) T \} + (1-\eta) \chi_n N_t^{\phi_n} / U'(C_t) \tag{1.27}$$

As opposed to the existing job matches, a new job match does not separate immediately and therefore do not feature firing cost in the Nash bargaining set up. The flexible wage for the new worker, W_t^{nf} is given by

$$W_t^{nf} = \eta\{\frac{P_t^i}{P_t} A_t Z_t^n - E_t \Lambda_{t+1|t}(1-\delta)T\} + (1-\eta)\chi_n N_t^{\phi_n}/U'(C_t) \tag{1.28}$$

The flexible real wage rates in equation (1.27) and (1.28) are obtained with the calibration of the mean of Z_t is 1 (approximately). We note that the flexible wage rate is highly correlated to the aggregate productivity shock, A_t. In response to the Shimer (2005) critique that the standard flexible wage model with search frictions cannot replicate the volatility in the labor market, several papers have adopted various approaches of introducing wage rigidity (see Gali (2011) and Hall and Milgrom (2010) for example). In this paper, I use a simple rigid wage setting approach by introducing a degree of real wage rigidity following Blanchard and Gali (2011). Wage rigidity is incorporated by means of a wage norm W as follows:

$$W_t(Z_t) = \epsilon_w W + (1-\epsilon_w) W_t^f \tag{1.29}$$

In Equation (1.29), the use of wage rigidity through a social wage norm W, is justified, according to Hall (2005) as a social consensus in selecting the equilibrium wage in a bargaining set with ϵ_w representing the degree of real wage rigidity such that $0 \leq \epsilon_w \leq 1$. As opposed to Hall (2005), which assumes that the wage norm is based on the immediate past quarter of wage, I use a norm that is sufficiently long looking backwards such that W is the wage rate paid on the long run expected aggregate productivity A_t and $\bar{Z}_t$.

1.4.6 Retail Sector and Pricing Friction

There is a continuum of monopolistic competitive final good producers, index by j $\in [0, 1]$. Final goods producers buy intermediate goods, $X_t(j)$ from the intermediate goods producing firms. They then transform the intermediate goods into final goods, $Y_t(j)$ and resell them to households. The production function of the final goods producer is as follows:

$$Y_t(j) = X_t(j); \tag{1.30}$$

In period t, a retailer sells $Y_t(j)$ units of the retail goods at the nominal price $P_t(j)$. The household consumes a bundle of retail goods, $Y_t = \left\{\int_0^1 Y_t(j)^{1-\frac{1}{\gamma}} dj\right\}^{\frac{1}{1-\frac{1}{\gamma}}}$ where γ is the elasticity of demand for the different type of retail goods in a Stiglitz formulation. The demand for each good is then given by

$$Y_t(j) = [\frac{P_t(j)}{P_t}]^{-\gamma} Y_t \tag{1.31}$$

where P_t is the price index given by

$$P_t = \int_0^1 P_t(j)^{1-\gamma} dj^{\frac{1}{1-\gamma}} \tag{1.32}$$

The price setting is a Calvo staggered pricing following the text book version in Gali (2009). During each period, a fraction, $(1-\theta_p)$ of the retailers can reset their prices optimally while the remainder use the last period's pricing. Each retail firm faces the same probability of changing the price over every period. The retail firm j then optimizes the following profit stream function when it sets the new price P_t^* given the price of the intermediate good, P_t^i.

$$E_t \sum_{k=0}^{\infty} \Lambda_{t+k|t} \theta_p^k [(\frac{P_t^*}{P_{t+k}})^{1-\gamma} Y_{t+k} - (1-\tau)\frac{P_{t+k}^i}{P_{t+k}} X_{t+k}(j)] \tag{1.33}$$

In the above equation, the real cost for the retailer is the price of a unit of intermediate good measured in terms of the final good. The government provides a subsidy to purchase the intermediate goods which is given by $1-\tau$. The first order condition with respect to P_t^* is as follows:

$$\begin{aligned}\sum_{k=0}^{\infty} \Lambda_{t+k|t} \theta_p^k (P_t^*/P_{t+k})^{1-\gamma} Y_{t+k} =& (1-\tau)\frac{\gamma}{\gamma-1} \\ & E_t \sum_{k=0}^{\infty} \Lambda_{t+k|t} \theta_p^k \{(P_t^*/P_{t+k})^{-\gamma} Y_{t+k}\}^{\frac{1}{1-\alpha}} \frac{P_{t+k}^i}{P_{t+k}}\end{aligned} \tag{1.34}$$

The government subsidy for the intermdiate good is such that it eliminates the monopolistic distortion by offsetting the markup in the steady state equilibrium such that:

$$1-\tau = \frac{\gamma-1}{\gamma} \tag{1.35}$$

The aggregate price transition is as follows where a proportion θ of the retailers maintains their last period's price while the remaining $1-\theta$ of firms reset their prices to the optimal price, P_t^*:

$$P_t = \theta_p P_{t-1} + (1-\theta_p)P_t^* \tag{1.36}$$

Equation (1.34) together with equation (1.36) gives rise to a simple log-linearized form of NK Phillips Curve:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa(\frac{\widehat{P_t^i}}{P_t}) \tag{1.37}$$

where $\kappa = \frac{(1-\beta\theta_p)(1-\theta_p)}{\theta_p})$.

1.4.7 Monetary Policy

The central bank conducts monetary policy using the following modified Taylor rule

$$\ln(I_t/I) = \rho_i ln(I_{t-1}/I) + (1-\rho_i)\rho_\pi \ln(\pi_t/\pi) + (1-\rho_i)\rho_y \ln(Y_t/Y) + \varsigma_t \tag{1.38}$$

where I, Y and π are the steady state values of the gross nominal interest rate, output and gross inflation rate respectively. With policy inertia, the central bank gradually adjusts nominal interest rate in response to movements in output and inflation. The exogenous monetary policy shock, ς_t is normally distributed with standard distribution $\sigma_{i,t}$.

1.4.8 Closing the Model

In closing the model, the aggregate consumption and match formation costs are equal to the aggregate output. I assume firing cost/tax is transferred to the workers.

$$C_t + H_n A_t Z_t^n M_t(j) + cV_t = Y_t \tag{1.39}$$

1.5 Solution

The model is solved by log-linearizing against the zero inflation steady state. The log-linearized system of equations is as given in the appendix 1.B.

1.5.1 Calibration and Steady State

The model is calibrated closely to the Krause and Lubik (2007) model with respect to the calibration of the parameters relating to the endogenous separations of labor matches. The steady state total separation rate δ_l is set to 0.10 as in Krause and Lubik (2007) which was based on the evidence from Hall (1995) and Davis et al. (1996) for the US quarterly worker separation rate. The exogenous job destruction rate of δ is set to 0.068, or 68 % of the total separations as suggested in Davis et al (1996). The endogenous separation rate then works out to 0.034 which is computed as $G(\underline{Z}) = (0.10 - 0.068)/(1 - 0.068)$.

The idiosyncratic shock distribution is assumed to be a lognormal distribution with mean 1 (as in Krause and Lubik (2007)) and the standard deviation 0.15 (the mid range in the literature of between 0.12 and 0.18). With the distribution calibrated, the various elasticities dependent on the distribution are computed. The steady state reservation productivity, $\underline{Z}$ is computed to be 0.76. The elasticity, $\frac{dlog\bar{Z}}{dlog\underline{Z}}$ is computed to be = 0.133. The elasticity $\frac{dlogG(\underline{Z})}{dlog\underline{Z}}$ is computed to be 14.8 while the elasticity of $\Phi(\underline{Z}_t)$ is computed to be 16.2. The steady state value for $\Phi(\underline{Z}_t)$ is computed to be 0.025T where T is the firing tax coefficient.

The discount factor β is calibrated to 0.99 to reflect the annual average interest rate of 4% . θ_p is set to 0.75 to reflect an average price duration of 1 year. The parameter κ is then implied to be 0.0858. I set the steady state N and F according to the evidence that average employment rate in post war US data is 0.59. The steady state job finding rate is set to 0.7. This implies a steady state U of 0.025. The steady state F = 0.615 giving a steady state unemployment rate U/F = 4.3%. I set ϕ_u to 10 (this was calibrated so as to achieve positive correlation between inflation and labor force rate)and ϕ_n to 1.

Gali (2011), drawing upon earlier evidence by Silva and Toledo (2009), calibrates the average cost of hiring a worker to be 4.5 % of the quarterly wage ie $\frac{c}{q(\theta)} = 0.045\bar{W}$ in steady state. Following Zanetti (2011), the productivity of new job matches, Z_n, is calibrated to be constant at the 95th percentile of the distribution. The adaptation cost parameter, H_n is implied from the steady state equations. The implied calibration is an adaptation cost of 25% of the productivity loss to a new job match and a total hiring cost of close to 30 %. This is in line with the empirical evidence as reported by Sakellaris (2000), Barron et al (1999) and Silva and Toledo (2011). I calibrate T to be 0.04 which correspond to a firing cost of

4% of output at steady state for a job match. The calibration reflects the relative insignificance of firing cost in the US Economy and is relatively in line with the fact that unemployment benefits constitutes on average 2 quarters duration at 6% of wage rate under regulation. This is also in line with Wesselbaum 2009 calibration of 0.05 to 0.10.

Wage rigidity follows Albertini and Fairise (2013) with ϵ_w set to 0.5. Blanchard and Gali (2010) assumed wage rigidities values of 0.5 to 0.9 on a quarterly basis whereas others like Faia(2008) and Albertini and Fairise(2013) uses a wage of 0.6. The elasticity of the matching function to U_t^o, μ is calibrated to 0.5 which is in line with Nagypal and Mortensen (2007)'s and Petrongolo and Pissarides (2001)'s argument for the vacancy elasticity of the matching function to be between 0.3 and 0.5. Under Hosio's condition and optimality, this implies that the workers' bargain share of wage, η to be 0.5.

The habit formation index, h is calibrated to be 0.65, in line with the calibrations in the literature. The relative risk adversity, σ is calibrated to 2. The monetary policy is calibrated as follows. The persistence of the interest rate reflecting policy inertia is calibrated to 0.7. This follows Walsh (2005) and Christiano et al (2014). The parameters governing the monetary rule are set as $\rho_\pi = 1.5$ and $\rho_y = 0.125$ which follows Taylor (1999) and Clarida et al (1999). The standard deviation of the innovation $\sigma_i = 0.025$ following Smets and Wouters (2007). I set the standard deviation of productivity shock to 0.075 with a persistence of 0.95.

1.6 Results

In this section, I evaluate the performance of the model of the artificial economy by examining the the respective standard deviations of the key statistics and the correlations between the key statistics as in Krause and Lubik (2007) and Ahrens et al (2014).

Table 1.2 reports the moments of interest from the model and from the quarterly empirical data for the US economy from 1964 to 2002. Comparing against the moments from the empirical data, the model performs reasonably well in addressing the issues highlighted in the basic endogenous separation model evaluated in Krause and Lubik (2007). Firstly, it achieves a strong negative correlation between unemployment and vacancies, thereby restoring the Beveridge curve relationship.

TABLE 1.2: Moments of the theoretical model

Standard Deviations	Data	Unconditional Moments	Monetary Shocks	Technology Shocks
Output	(1.62)	(0.86)	(0.21)	(0.84)
Real Wage	0.69	0.53	0.80	0.51
Inflation	0.19	0.53	0.17(0.19)[2]	0.54(0.27)[2]
Employment	0.60	0.75	0.95	0.74
Unemployment	6.9	10.9	12.3	10.8
Vacancy	8.27	10.0	10.0	10.0
Tightness	14.96	9.7	10.2	9.63
Job Creation Rate	2.55	6.5	6.2	6.42
Job Destruction Rate	3.73	0.95	0.80	0.96
Labor Force	0.3	0.62	0.72(0.2)[2]	0.62(0.39)[2]
Correlations				
U,V	-0.96	-0.99	-0.99	-0.99
JCR, JDR	-0.36	-0.97	-0.99	-0.97
Labor Force, Y	0.30	0.05	0.78(0.31)[2]	-0.02(0.02)[2]
Y,Inflation	0.39	-0.60	0.79(0.4)[2]	-0.68(0.6)[2]

[1] The standard deviations are relative to the standard deviation of output except for output.
[2] (.) for Labor Force represents values of US Economy taken from Gali (2011).

The job creation rate and job destruction rate are now negatively correlated. The job creation rate is much less volatile than highlighted in the Krause and Lubik model and is in line with the empirical moment. These improvements in the model are achieved with an average wage rate that is in line with the volatility of the historical average wage rate, a low firing cost and worker turn-over cost (training and adaptation cost)that are in line with the US economy. However, the model fails to produce the positive correlation between output and inflation as pointed out by Krause and Lubik (2007). The moments for inflation conditional on monetary shocks matches relatively well the empirical data, although it is more positively correlated than the empirical data. However, the technology shock in the model produces a strong counter-factual negative correlation between inflation and output. However, it is important to note that the model does not feature capital and other shocks impinging on the US economy. An important shock that is not studied in the model is that of investment specific technology shock. A richer model with capital and investment specific technology shocks would yield further insights into this issue.

The model matches relatively well with regards to the unconditional moments for labor force participation although the standard deviation is higher than the standard deviation in the empirical data. The conditional moments with respect to technology shocks are relatively in line with the empirical data, showing acyclicality and a slightly stronger volatility. However, conditional on monetary shocks, labor force participation rate is much more volatile and procyclical than the empirical data. The latter issue is however inherent in models in Campolmi and Gnocchi (2014)'s and Gali (2011)'s versions of endogenous labor participation with regards to consumption shocks. This is because in the model with labor matching, the highly volatile and procyclical job finding rate dominates the counter effects from income effects. More frictions are needed in the model. Erceg and Levin (2013) features adjustment cost for labor participation. Christiano et al(2014) features habit formation for home production. Another aspect is that of labor search effort. It could be argued that procyclical labor search arising from the increase in job finding rate could manifest in increase search effort and labor force participation rate with the increase in search effort substituting for the labor participation rate.

The impulse response functions to an interest rate rate policy shock of 0.25% are given in Figure 1.1 while the impulse response functions to a technology shock of 0.75% are given in Figure 1.2. A policy shock in the form of an interest shock reduces consumption and results in a lower inflation. Both employment rate and labor force participation rate decrease. The earlier is a combination of the lower job finding rate and a higher separation rate. The lower labor force participation rate is the result of a lower employment rate while the increase in searching workers is not strong enough to counteract the decrease in the employment rate resulting in a labor force participation rate that is procyclical and volatile but less volatile and procyclical than the employment rate. This is also partly because the income effect is not strong enough. The property of the Beveridge curve where u,v move strongly in opposite directions in shown in Figure 1.1c. Likewise, the impulse response function for job creation and destruction shows strong negative correlation in Figure 1.1d.

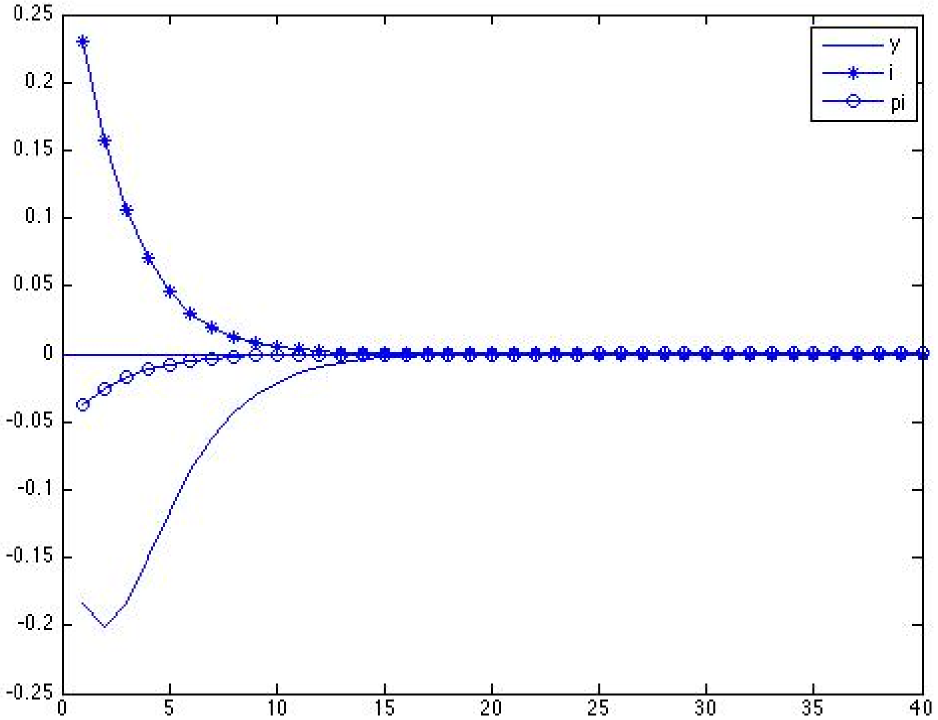
The impulse response functions for technology shocks in Figure 1.2 shows a typical response to technology shocks. Consumption increases to a positive technology shock, a negative inflation results because of the stickiness of nominal price in the Calvo setting. Employment reduces as firms reduces output because the consumption increase is not strong enough due to habit formation and nominal price rigidity. Labor force participation reduces due to the income effect over as well as the lower job finding rate. The negative correlation between u,v and the job creation and job destruction rates are demonstrated in the impulse response functions.

1.7 Conclusions

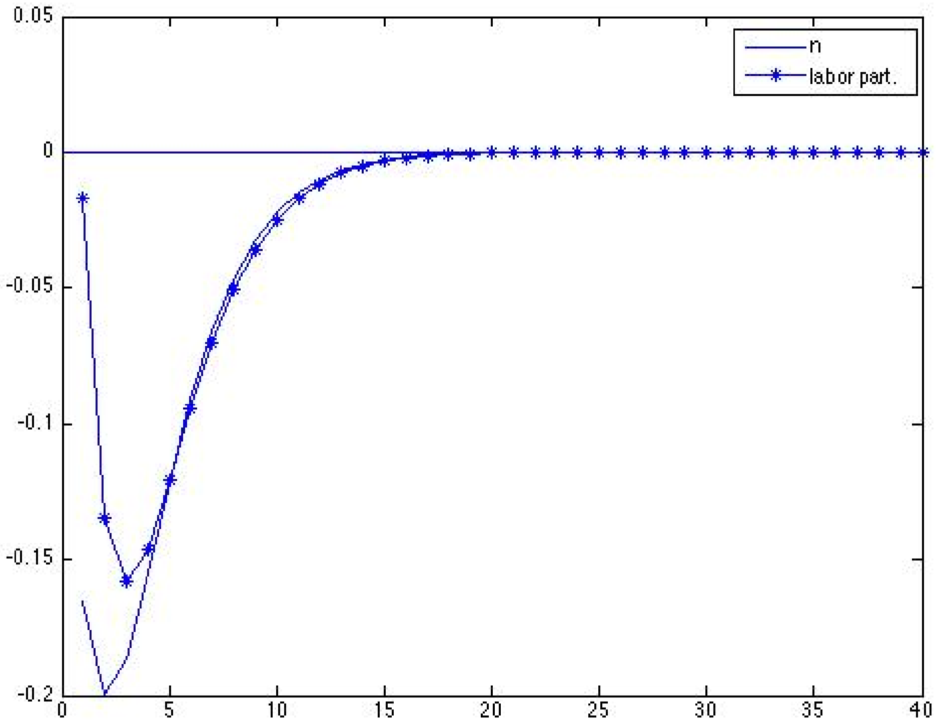
The model that is developed here brings together in a New Keynesian model, endogenous job separations, endogenous labor participation rate and worker turn over costs. The basic endogenous separation model exhibits several issues as highlighted in Krause and Lubik (2007). Yet, endogenous separation models are important in the study of firing costs and labor institutions. There are several extensions of the basic Krause and Lubik (2007) model (see Zanetti (2011), Campolmi and Faia (2011) and Ahrens et al. (2014)) which rely on high separation costs and /or wage rigidity to resolve some of the issues with varying degrees of success.

The model presented here achieves performance improvements in resolving three of the hurdles: a) the positive correlation between unemployment and vacancies, b)the positive correlation between the job creation rate and job separation rates and c) the high volatility rate of the job creation rate. The model also exhibits standard deviation for tightness, unemployment rate and vacancy rate are in line with the data with a wage rate that is relatively as volatile as the empirical average wage rate.

The current literature for policy evaluation with respect to labor institutions and unemployment insurance emphasizes job separation costs (see Zanetti (2011), Campolmi and Faia (2011) and Ahrens et al.(2014)). Yet, as highlighted in Wesselbaum (2009), job separation costs in the US economy are low and cannot resolve the issues in the basic endogenous job separation model. Significantly, as pointed out in empirical studies on labor hiring (see Sakellaris (2000) and Barron(1999)) labor match formation costs include a significant component in the form of adaptation costs and productivity losses as well as training costs. These costs are mostly ignored in models (except for a few research work like Silva and Toledo (2009) and (2011)). This paper contributes to the literature by bringing these cost components into the endogenous job separation model with an improvement

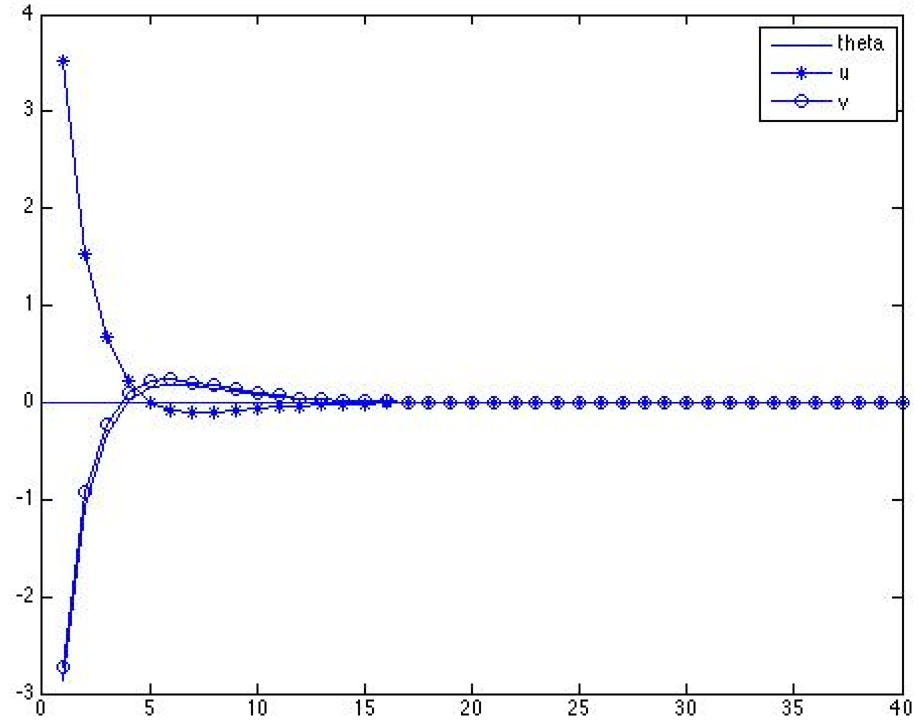


(a) Y, π and i

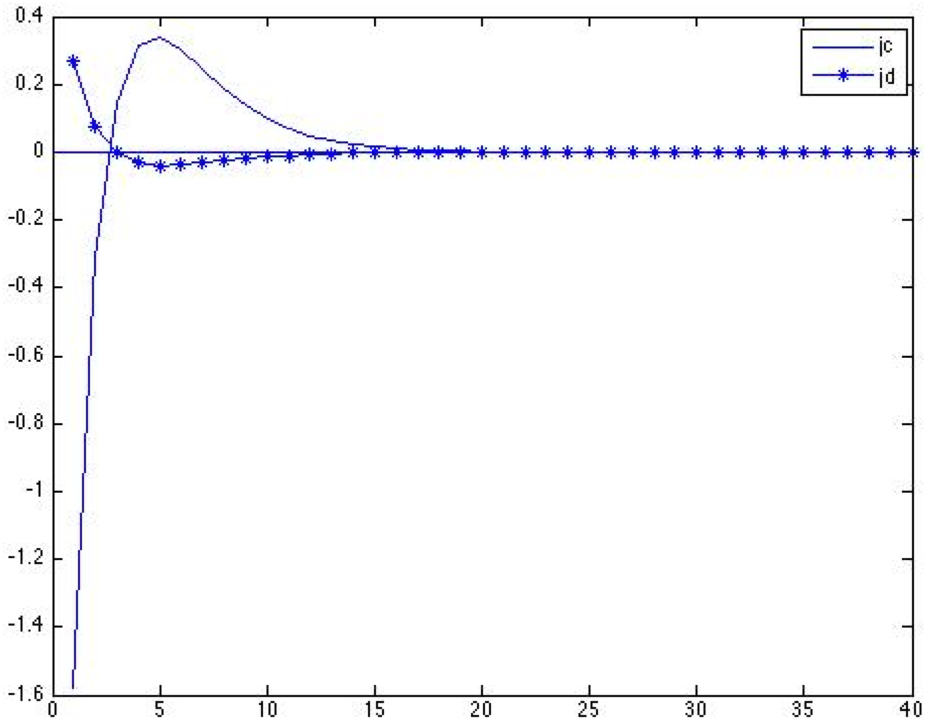


(b) labor force part. and employment

FIGURE 1.1: Impulse response to interest rate shock of 0.25%

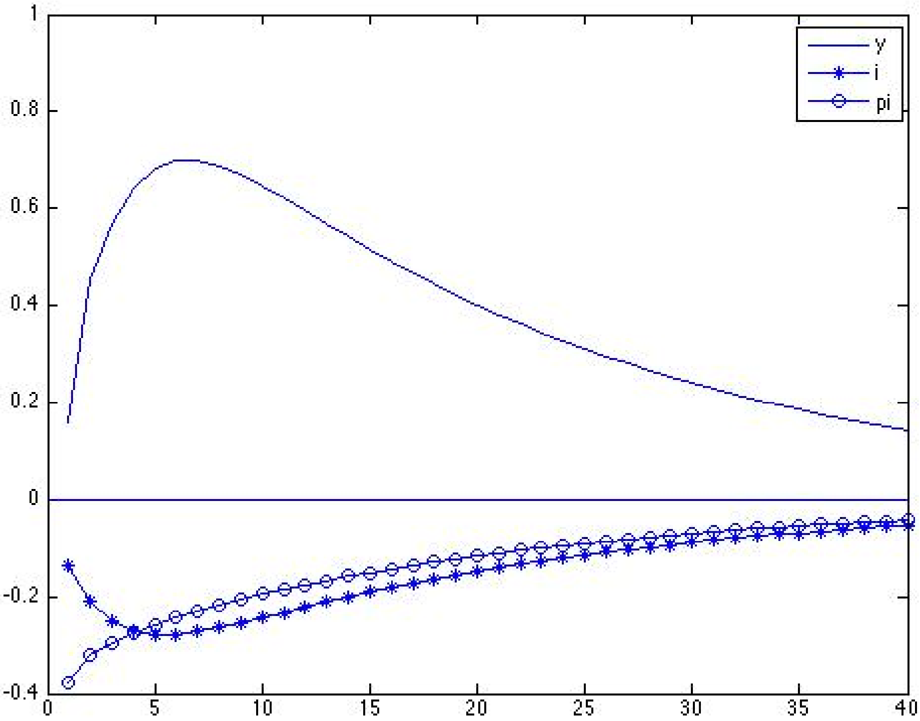


(c) u, v and θ

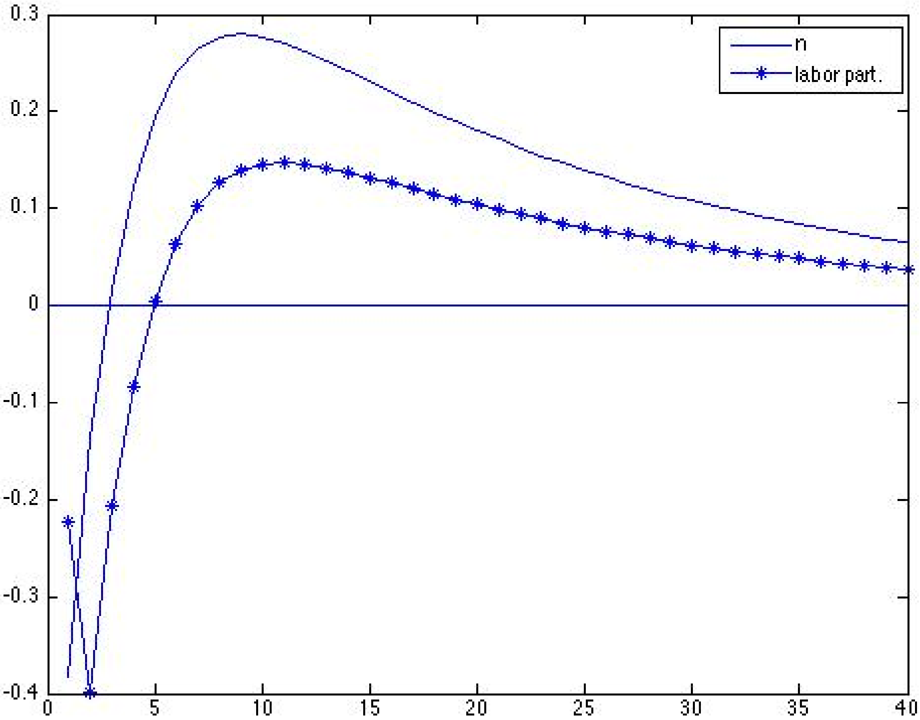


(d) job creation and job destruction

FIGURE 1.1: Continued - Impulse response to interest rate shock of 0.25%

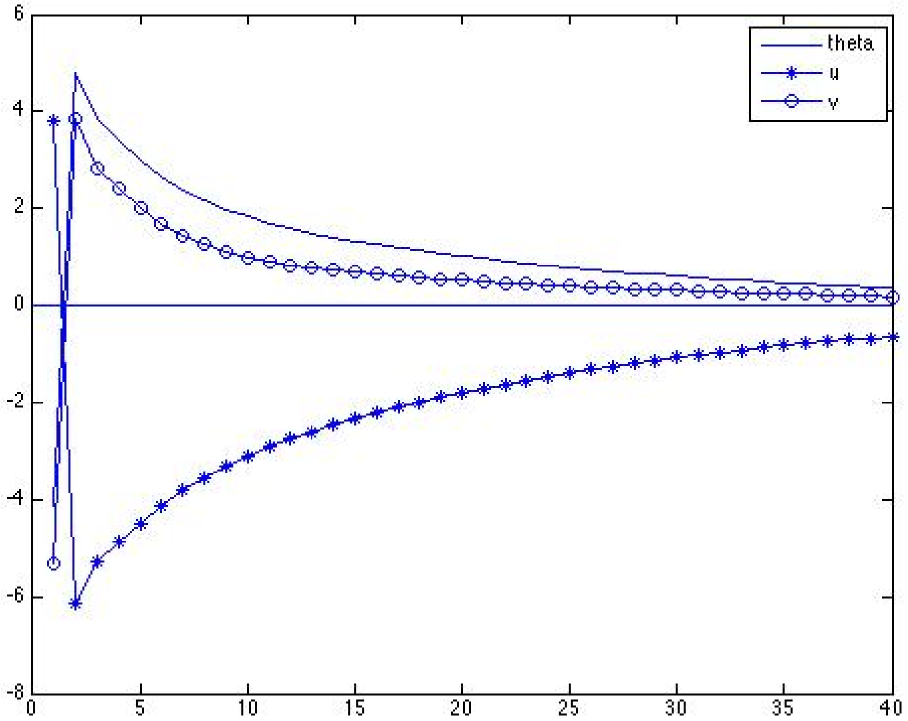


(a) Y, π

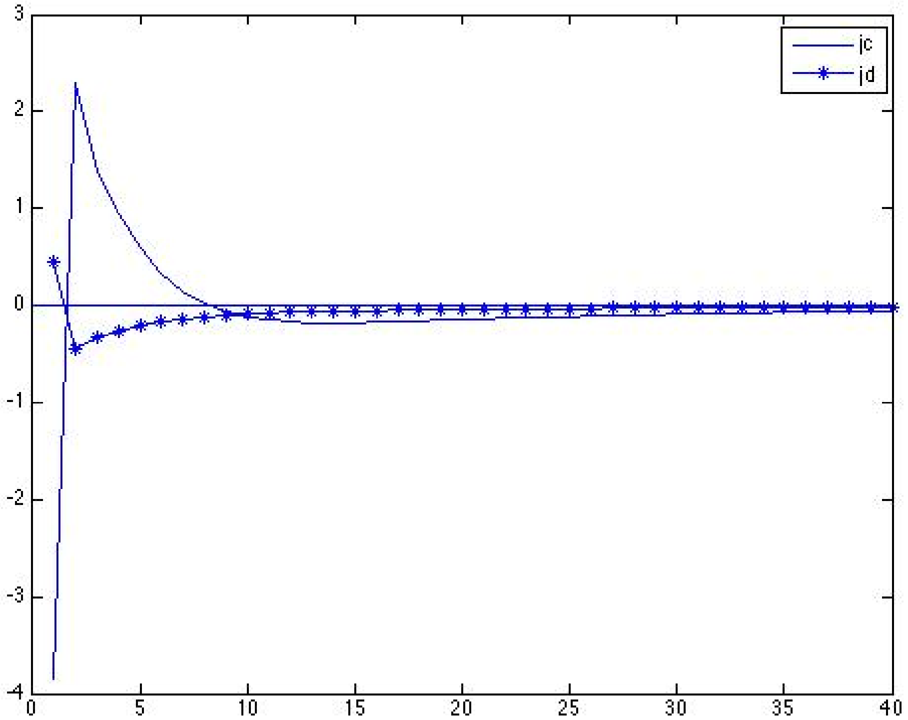


(b) labor force part. and employment

FIGURE 1.2: Impulse response to technology shock of 0.75%



(c) u, v and θ



(d) job creation and job destruction

FIGURE 1.2: Continued - Impulse response to technology shock of 0.75%

in performance. The model shows that in place of separation costs, worker replacement costs from productivity losses due to adaptation costs and training in new hires can play an important role for endogenous separation models.

The model does not resolve the negative correlation between the inflation rate and output as highlighted in the unconditional correlation moment between the inflation rate and output. A closer examination shows that this arises from the negative correlation between inflation and output with respect to technology shocks. However, we need to view this in the context of the model featuring only labor and that capital investment and investment technology specific shocks have been abstracted away. Further investigations can be conducted in a richer model featuring these elements. Campolmi and Gnocchi (2014) and Nucci and Rigg (2014) also introduced other shocks like preference shocks that change the composition of the shock contribution in order to bring the model performance closer to data.

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Appendix

Appendix 1.A Calibration

Parameter	Description	Value	Source
β	Discount factor	0.99	
γ	Elasticity of substitution of Final Goods	6	markup of 20%
θ	Fract. of Producers not able to reset price	0.75	Average wage duration of 1 year
μ	Elasticity of matching function to u	0.5	Petrongolo and Pissarides (2003)
η	Worker's share of wage bargain	0.5	Hosios Condition - Nagypal and Mortensen
T	Firing Tax Coefficient	0.04	around 2 quarters of 6% of wage rate
H_n	Adaptation Cost and Training Cost	0.25	Steady State Eqs and Sakellaris (2000)
ϵ_w	Wage Rigidity	0.5	Blanchard and Gali (2010)
ϕ	Elasticity of ν_n	1	target volatility of wage rate
ϕ_u	Elasticity of ν_u	10	target correlation of labor part. with Y

Table 1.A.1: Calibration targets -1

Parameter	Description	Value	Source
$\frac{c}{q(\theta)}$	Average cost of filling a job	0.045 quarterly wage	Silva and Toledo(2005)
$f(\theta)$	Steady state job finding rate	0.7	Gali(2011)
δ_l	Steady state total separation	0.10	Krause and Lubik(2007)
δ	Exogenous Job separation rate	0.068	Davis et al(1996)
$\mu(Z)$	Mean of G(Z)	1	Krause and Lubik(2007)
σ_z	Standard Deviation of G(Z)	0.15	Mid range in literature
h	index of external habit formation	0.65	Lower range in literatue
ρ_{pi}	monetary response to inflation	1.5	Taylor(1999) Clarida et al(1999)
ρ_y	monetary response to output	0.125	Taylor(1999) Clarida et al(1999)
ρ_i	interest rate smoothing	0.7	Christiano(2014) Walsh(2005)
ρ_a	technology shock persistence	0.95	
σ_a	standard deviation of technology shocks	0.075	
σ_i	standard deviation of monetary shocks	0.025	Smets and Wouters (2007)

Table 1.A.2: Calibration Targets -2

Appendix 1.B Loglinearized Model

The log-linearized system of equations for the economy is presented in this section.

(a)NK Phillips curve in real marginal costs:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa(\widehat{\frac{P_t^i}{P_t}}) \tag{1.40}$$

In equation (1.40), the inflation rate $\pi_t = logP_t/P_{t-1}$, $\kappa = \frac{(1-\beta\theta_p)(1-\theta_p)}{\theta_p})$ and $\widehat{(\frac{P_t^i}{P_t})} = logP_t^i - logP_t$.

(b)Intertemporal substitution equation for bonds:

$$-\hat{i}_t = \left(\frac{1}{1-h}c_t - \frac{h}{1-h}c_{t-1}\right) - E_t\left(\frac{1}{1-h}c_{t+1} - \frac{h}{1-h}c_t\right) - E_t\pi_{t+1} \tag{1.41}$$

where $\hat{i}_t = i_t + \log\beta$.

(c)Monetary policy rule (1.38)

$$\hat{i}_t = \rho_i i_{t-1} + (1-\rho_i)\rho_\pi \pi_t + (1-\rho_i)\rho_y y_t + \varsigma_t \tag{1.42}$$

(d)Production function:

$$y_t = a_t + \frac{(1-\delta)N\bar{Z}}{Y}(-\frac{G(Z)}{1-G(Z)}\eta_{\underline{z}}^G \underline{z_t} + n_{t-1} + \eta_{\underline{z}}^{\bar{z}}\underline{z}_t) + \frac{f(\theta^o)U^oZ^n}{Y}((1-\mu)\theta_t^o + U_t^o) \tag{1.43}$$

(e)Labor Force Participation

$$f_t = \frac{U}{F}u_t + \frac{N}{F}n_t \tag{1.44}$$

(f)End of period unemployment rate

$$u_t = \frac{f(\theta^o)}{1-f(\theta^o)}(1-\mu)\hat{\theta}_t^o + u_t^o \tag{1.45}$$

(g)Labor transition equation

$$n_t = (1-\delta)(1-G(\underline{Z}))\left[\frac{-G(\underline{Z})}{1-G(\underline{Z})}\eta^G_{\underline{z}}\underline{z}_t + n_{t-1}\right] + \frac{f(\theta^o)U}{(1-f(\theta^o))N}\{(1-\mu)\hat{\theta}^o_t + u^o_t\} \tag{1.46}$$

where $\eta^G_{\underline{z}}$ is the elasticity of $G(\underline{Z}_t)$ with respect to the cut off reservation productivity $\underline{Z}_t$.

(h)Job creation equations

$$\mu\theta^o_t = \frac{1}{\frac{c}{q(\theta)}}(Z_n(\frac{\hat{P}^i_t}{P_t}+a) - \overline{W_n}w_{n,t} - H_nZ_n(\frac{P^i_t}{P_t}+a) + \bar{\xi}\xi_t) \tag{1.47}$$

(i)Definition of $\widehat{\xi_t}$

$$\widehat{\xi_t} = m_t - m_{t+1} - \frac{G(\underline{Z})}{1-G(\underline{Z})}\eta^G_{\underline{z}}\underline{z}_t + \frac{\beta(1-\delta)}{\bar{\xi}}(\bar{Z}(\frac{\widehat{P^i_{t+1}}}{P_{t+1}} + a_{t+1} + \eta^{\bar{Z}}_z z_{t+1}) - \overline{W(\bar{Z})}w(\overline{z_{t+1}}) - \Phi\eta^{\Phi}_{\underline{z}}\underline{z}_{t+1}t + \bar{\xi}\xi_{t+} \tag{1.48}$$

(j)Definition of m

$$m = \left(\frac{1}{1-h}c_t - \frac{h}{1-h}c_{t-1}\right) \tag{1.49}$$

(k)Average Wage

$$\begin{aligned}\hat{\bar{w}}_t =&(1-\epsilon_w)\Bigg\{\frac{\eta\bar{Z}}{\bar{W}}\left((\widehat{\frac{P^i_t}{P_t}}) + a_t + \eta^{\bar{z}}_{\underline{z}}\underline{z}_t\right) + \frac{\eta T\bar{Z}}{\bar{W}}\eta^{\bar{z}}_{\underline{z}}\underline{z}_t - \frac{\beta\eta(1-\delta)T}{\bar{W}}[m_t - E_t(m_{t+1})] \\ &+ \frac{(1-\eta)\bar{M}\chi N^{\phi}}{\bar{W}}(m_t + \phi n_t)\Bigg\}\end{aligned} \tag{1.50}$$

(l)Wage of new hired

$$\begin{aligned}\hat{w_{nt}} =&(1-\epsilon_w)\Bigg\{\frac{\eta\bar{Z}_n}{\bar{W}_n}\left((\widehat{\frac{P^i_t}{P_t}}) + a_t\right) - \frac{\beta\eta(1-\delta)T}{\bar{W}_n}[m_t - E_t(m_{t+1})] \\ &+ \frac{(1-\eta)\bar{M}\chi N^{\phi}}{\bar{W}_n}(m_t + \phi n_t)\Bigg\}\end{aligned} \tag{1.51}$$

(m)Job destruction equation

$$\mu\theta^o_t = \frac{1}{\frac{c}{q(\theta)}}\{Z_n((\widehat{\frac{P^i_t}{P_t}}) + a_t) - \underline{Z}((\widehat{\frac{P^i_t}{P_t}}) + a_t + \underline{z}_t) - \overline{W_n}w_{n,t} + \overline{W(\underline{z})}\underline{z}_t - T\underline{Z}\underline{z}_t - H_nZ_n((\frac{P^i_t}{P_t}) + a_t) \tag{1.52}$$

(n)Labor Participation equation

$$\phi_u u_t^o = -m_t + (1-\mu)\theta_t^o + vn_t \tag{1.53}$$

(o) Definition of vn_t (value function of a new hire to the household)

$$vn_t = \frac{W_n}{V_n} w_{n,t} - \frac{\chi \bar{M} N^{\phi}}{V_n}(m+\phi n) + \frac{\beta(1-\delta)V_e}{V_n}(-G(Z)/(1-G(Z))\eta_z^G z_{t+1} + m - m_{t+1} + ve_{t+1}) \tag{1.54}$$

(p)Average value of an employed worker to the household

$$ve_t = \frac{\bar{W}}{V_e}\bar{w}_t - \frac{\chi \bar{M} N^{\phi}}{V_e}(m+\phi n) + \frac{\beta(1-\delta)V_e}{V_e}(-\frac{G(Z)}{(1-G(Z))}\eta_z^G z_{t+1} + m - m_{t+1} + ve_{t+1}) \tag{1.55}$$

(q)Aggregate quantities

$$y_t = \frac{C}{Y}c_t + \frac{\frac{c}{q(\theta)}f(\theta)U}{(1-f(\theta))Y}(\theta_t + u_t^o) + \frac{H_n Z_n f(\theta) U^o}{Y}((1-\mu)\theta_t + u_t^o + a_t + \frac{\widehat{P_t^i}}{P_t}) \tag{1.56}$$

Chapter 2

Frictional Physical Capital and Labor Markets

2.1 Abstract

In this paper, I worked with a Real Business Cycle model incorporating matching frictions in the physical capital and labor markets in the presence of fixed sunk in cost in both labor and capital matching to evaluate the implications of such frictions in the generation of key business cycle characteristics. This is in view of the issues highlighted in Shimer(2005) that a typical labor matching model is not able to generate the empirical characteristics of a business cycle. With the model incorporating matching frictions and adjustment costs documented in empirical studies in Barron(1996) et al in a model where labor supply is endogenous and a Greenwood, Hercowitz and Huffman utility preference, I evaluate the performance of the model and conclude that the model can generate the volatility of the market tightness in the empirical data despite a flexible wage and an opportunity cost for labor that is highly procyclical and volatile. Nevertheless, investment exhibited very little amplification effect. I further subject the model to news shock to evaluate the impact from the use of unmatched capital and labor to news shocks.

2.2 Introduction

Labor market frictions in the form of matching friction is well accepted amongst researchers in explaining the presence of a pool of unmatched workers who are available yet unemployed in the production process. However, the incorporation of the Diamond, Mortensen and Pissarides matching framework in DSGE models to model labor market is problematic in that it is generally not able to replicate the business cycle characteristics exhibited in the empirical data.

The physical capital market exhibits a similar trait as the labor market. In the literature, there are studies on used physical capital market as well as inventory management which includes unsold durable goods such as equipment and machineries used as capital goods. The physical capital market resembles that of labor market with unsold inventories and "old" physical capital that are not "matched" to entrepreneurs and firms due to separation. The reasons for the matching frictions are quite similar. Physical capital is often specific to a location whether it is an office or a manufacturing plant. Machineries are also specific to a particular function. Like the labor market, there are vacant office buildings and inventories that takes time to be sold and employed by firms. Likewise there are physical capital that are separated from matches and rejoin the pool that are to be re-matched. There are substantive literature on inventory management and to a much lesser extent used physical capital.

Matching costs in the form of fixed sunk in cost have been demonstrated in two papers by Silva and Toledo (2009) and (2011) and discussed in Pissarides (2009) and Nagypal and Mortensen (2009) as one mechanism in the partial resolution of the volatility puzzle highlighted in Shimer (2005). Empirical studies by Sakellaris (2000), Barron et al (1999) on adjustment costs highlight that substantial training and adaptation costs are incurred in the first quarter of a newly hired worker and in the case of installation of equipment, productivity loss is incurred. In the matching models, these costs in addition to direct search costs affect the volatility of matching rate under the assumption of free-entry in creation of vacancies.

As an extension, I address the question of how substantive is the effect of the availability of the excess capacity in the economy in the form of unmatched capital and labor. Theoretically, the economy can make use of these resources by increasing vacancies/search activities when faced with surprise shocks as well as news shocks.

There are substantial research work into models involving news shocks and getting the models to generate Pigou cycle characteristics which basically requires getting consumption, investment, output and employment rate to move in tandem in response to news shocks. Beaudry and Portier (2003) first highlighted the difficulty in producing Pigou Cycles in a one sector RBC model. The literature also includes other works by Christiano et al (2008), Karnizova (2011), denHaan and Kaltenbrunner(2009), denHaan and Lozej(2010) in addressing the issues of producing a Pigou Cycle in a RBC model with respect to a news shock.

The presence of a highly volatile inventory investment in the economy has been the focus of several research works which attempt to evaluate its significance on the business cycle. While I study the matching model in the narrower perspective of finished physical capital goods, some of the perspective and model performance can be related to the empirical behavior of finished durable good inventory and its correlation to the business cycle behaviors of sales and output. Although the model in this paper is different from the stock elastic demand inventory model of Bils and Kahn (2000) by focussing on matching frictions, a matching model shares some similarity with the stock elastic demand model in the availability of unsold stock and how the sale of the unsold stock is dependent on the inventory stock. This constitutes an additional area of study in this paper.

2.3 Literature

In seeking to explain labor market, current research works often incorporate a frictional labor market into business cycle models in the form of a DMP matching mechanism. Yet, this approach has met with a major challenge highlighted in Shimer (2005). In that paper, Shimer demonstrated the inability of the DMP matching model to reproduce the empirical behavior of the labor market in business cyles. The simple DMP model with Nash wage bargaining generates labor market tightness that is too small compared to the empirical data. To resolve this, an often used approach is to incorporate a degree of wage rigidity often in the form of staggered wage contracts, wage norms and Hall and Milgrom (2008)'s alternate bargaining mechanism. The approach has however been met with criticisms - see Pissarides (2009) and Haefke et al (2013). In particular, the authors argue that starting wage which is critical in influencing the hiring rate of worker is very flexible with an elasticity of close to one with labor productivity.

A partial resolution in the amplification of labor market tightness is that of match fixed cost as suggested in Nagypal and Mortensen (2007), Pissarides (2009), Siva and Toledo (2009) and (2011) and others. Siva and Toledo (2009) and (2011) draw upon the empirical information from Barron (1999) and Sicilian (2001) on labor costs in the form of training costs. Both of these studies reveal insignificant effect on starting wages from training costs (of less than 5%). Hence the training costs are modelled as sunk in costs not subject to worker and firms bargaining. Recent works on labor hiring costs which includes Dube et al (2010) and Samuel and Mirjam (2015) also highlighted training and adaptation/disruption costs. An earlier study, Sakellaris (2000) documents the decrease in productivity at the plant level for the period following an investment spike or employment spike, highlighting empirical evidence of adaptation cost and disruption costs associated with the introduction of newly hired workers and the installation of capital. The initial period of adaptation and disruption results in an output productivity decline in the immediate period of hiring and installation.

The earlier approaches to augment the volatility of market tightness and unemployment in the models also rely on calibrating a high level for the disutility of labor and replacement rate. Nagypal and Mortensen(2007) suggests the calibration of the level of replacement rate and disutility to be sufficiently high of around 0.72. On the other hand, Hagedorn and Manovski(2008) calibrated a model with a level of 0.95. The approaches assume most importantly that the level of labor disutility and replacement rate are also constant and does not comove with labor productivity, thus inducing a greater degree of wage rigidity to labor productivity. Chodowrow-Reich and Karababounis (2016) proposes instead that the level of labor disutility comoves strongly with labor productivity using standard formulation of utility functions.

Additionally, in the standard Nash bargain wage formulation, a portion of the wage accounts for the outside option of finding a job in the second period. This portion accounts for about 30% of the wage (in Shimer (2005)) and is a very volatile component that comoves very strongly with labor productivity due to its dependence on the fast moving job finding rate. To reduce the degree of this co-movement, researchers often introduce wage rigidity through labor bargaining, norm wages and strategic bargaining (Hall and Milgrom(2008)) - see Christiano et al. (2014), Gali (2010) for examples. However, if the disutility of job search and labor participation is accounted, the outside option of finding a job would have been offset by the disutility of labor participation in a competitive search setting. Gali (2011) modeled labor participation in a NK setting where the outside option of job search is offset by the disutility of labor participation. However, Nucci and Riggi(2014), Campolmi and Gnocchi(2014) discusses NK models with particpation rate while maintaining the outside option and imposes wage rigidity in the form of norm wages. Christiano et al(2014) develops a model of labor participation with credible strategic bargaining following Hall and Milgrom(2008).

The treatment of physical capital market as a market with matching frictions giving rise to a pool of both available and unmatched capital goods that includes separated capital goods has been explored in works dealing with re-used capital. Empirical studies in the re-used capital goods like Eisfeldt and Rampini (2005) who studied the reallocation of capital highlight the procyclicality and significance of re-used capital in business cycles. According to Eisfeldt and Rampini (2005), the re-allocation of capital including merger and acquisition makes up approximately one quarter of total investment per quarter. Around one third of the re-allocation comprises of direct sales of plant and equipment between firms. Kurmann and Petrosky-Nadeau (2007) built a RBC model with a physical capital market with matching frictions. However the model when calibrated does not exhibit any significant deviation from a standard RBC in performance. Ottonello (2015), on the other hand, used a physical capital matching model to highlight that matching frictions inhibiting reallocation results in slow economic recovery after a recession.

The physical capital market in the DSGE models of Kurmann and Petrosky-Nadeau (2007) and Ottonello (2015) focused on re-used capital but implicitly implies unsold inventory of capital goods as finished durable goods. As such, the models should address empirical behavior of inventory and sales for durable goods exhibited in the data. Bils and Kahn(2000) explored a stock elastic demand model for finished goods product, which shares similar characteristics to a matching model. Recent works on the application of matching models on finished goods include Wasmer and Petrosky-Nadeau (2014), Bai et al (2012). denHaan (2013) evaluated the volatility and persistence amplification arising from the goods market frictions while confronting the empirical behavior of inventory and sales in the business cycle. When disciplined against the empirical behavior of inventory, he concluded that the goods market frictions are quantitatively not very important. While the scope of investigation in this paper is limited to the physical capital goods market, the inventory behavior of physical capital goods should not deviate too significantly from the inventory behavior of durable goods.

Finally, as an extension of the model, we explore the implication of the availability of a pool of unmatched capital goods (both separated and unsold inventory of finished goods) to news shocks in addition to neutral technology shocks. The difficulty of generating Pigou Cycles in which consumption, investment, employment and output rises together in reaction to good news was first highlighted in Beaudry and Portier (2003). Several papers approached the problem from several angles. Christiano et al(2008) developed a model of internalised habit formation, investment adjustment cost and variable capital utilisation in a frictional monetary model with an accomodating monetary authority. Beaudry and Portier (2003) utilised a multi-sector model approach. Krusell and McKay(2010) in a review article suggested the use of labor matching model over the use of a GHH ie Greenwood et al(1988) preference model to eliminate the wealth effect in the supply labor which is essential in generating the increase in labor supply. DenHaan and Kaltenbrunner(2009) and DenHaan and Lozej(2010) explored labor matching model with the latter in an open economy context to reproduce pigou cycles. Linking news shocks and inventory facts, Crouzet and Oh(2014) estimated a DSGE model which reported that news shocks play an insignificant part in the business cycle.

2.4 Model

I augment the basic RBC model in Rebelo and King (2000) with a physical capital market and a labor market with matching frictions. This is along the line of models by Kurmann and Nadeau (2007) and Ottonello (2015). There are two types of agents in the model, households and firms. Households supply labor and capital. The latter is converted from consumption goods into capital goods. Households hold unused capital goods ie they hold both an inventory of unsold capital goods waiting to be matched to firms as well as served as a liquidity provider to firms by buying the unused capital goods. Firms are employers of labor and renters of capital. Firms produce consumption goods which households buy for consumption or buy to convert to capital goods. Matching frictions exists in the capital market and labour markets. The modelling of households holding inventory and leasing capital model can be adapted into a capital producing goods using the same argument as Greenwood et al (2000) and is used here as a simplification of the model.

2.4.1 Timing of model

Each time period consists of the following activities. At the beginning of the period, the aggregate productivity is observed. Hiring follows with both households and firms aware of the aggregate productivity, similar to the line of work of Gali and Blanchard (2010) and Gali (2010). Production then proceeds after the hiring. Separations of labor and capital employed by the firm and depreciation of capital occurs after the production finishes, The household then decide how much to invest as capital goods and this is followed by the matching process of the physical capital with the firms. Capital can only be used in the next period production which is in line with the one period ahead install time for capital in most of the literature.

2.4.2 Representative Household

Households in the economy are modeled as a large representative household as in Merz (1999) with complete insurance of consumption amongst members. The representative household consumes and finances its consumption from wage, unemployment benefits, profits from firms which the representative household owns and rental of capital. The representative household smoothes its consumption by converting some of the consumption goods into capital stocks for rental income from the firms. The representative household discounts expected flow utility of consumption $U\big(C_t\big)$ over consumption C_t with a time discount factor of $0 < \beta < 1$ where β is the time discount factor. The lifetime utility function which the houshold optimises is as follows:

$$E_0 \sum_{t=0}^{\infty} \beta^t U\big(C_t, N_t, U_t^o\big) \tag{2.1}$$

subject to a period budgetary constraint of

$$C_t + Inv_t \leq W_t N_t + b(1 - N_t) + r_{k,t} K_t + \pi_t \tag{2.2}$$

In equation (2.2), the household consumption C_t and investment in physical capital, Inv_t, is financed by revenue from the wage, W_t from N_t employed households, the unemployment benefits b, from its unemployed workers and the return from the capital that is rented to firms. The labor force is normalized to 1. At the beginning of the period, the household decides on the number of unmatched members to participate in the job search and this is denoted by U_t^o incurring a disutility from the search activities. The household also owns(but does not decide on the portfolio holding) the firms which yield the return of profits from the firm π_t. The representative household maximizes consumption by its choice of investment Inv_t. The household holds both inventory of unmatched capital assets, L_t and capital assets that is rented out to the firms, K_t. The transitions for both labor and capital are subject to separations as well as market frictions in the labor and capital markets with the probability of finding a match given by $f_n(\theta_{n,t})$ and $f_k(\theta_{k,t})$ respectively. Both are functions of the respective market tightness, $\theta_{n,t}$ and $\theta_{k,t}$. The household capital asset that is successfully rented out to firms, K_t is subject to depreciation, δ_k and exogenous separation, s_e. In addition, successful matches at the end of the period for the liquid assets, $f_k(\theta_{k,t})L_t$ augments the next period capital that is rented out to the firms:

$$K_{t+1} = (1-\delta_k)(1-s_e)K_t + (f_k(\theta_{k,t}))L_t \tag{2.3}$$

The amount of investment spending in the economy is hence $(f_k(\theta_{k,t}))L_t$. The liquid asset that the houshold holds for matching consists of unmatched liquid assets from the last period (as represented by the first term on the RHS in equation 2.4), investment goods produced this period and recovered capital from the exogenous separation which is subjected to a recovery rate of ψ. The depreciation rate of the unmatched asset is δ_k.

$$L_t = (1-f_k(\theta_{k,t-1}))(1-\delta_k)L_{t-1} + Inv_t + \psi(1-\delta_k)s_eK_t \tag{2.4}$$

Firms labor stock evolves as follows:

$$N_t = (1-\delta_n)N_{t-1} + f_n(\theta_{n,t})U_t^o \tag{2.5}$$

where labor stock is subject to match separations of labor at the rate of δ_n. U_t^o is the number of unemployed household members at the beginning of period participating in the labor matching market.

The household's per period utility function is assumed to take the following form:

$$U(C_t, N_t, U_t^o) = \frac{(C_t - \nu_n(N_t)^{1-\sigma}}{1-\sigma} - \nu_u(U_t^o) \tag{2.6}$$

In equation 2.6, the parameter $1/\sigma$ is intertemporal elasticity of substitution. $\nu_n(N_t)$ is the disutility of labor associated with the household supplying N_t of labor and $\nu_u(U_t^o)$ is the disutility of labor search costs. The formulation of the utility functions draws from Greenwood et al(1988) which removes the effect of wealth on the disutility of labor. With this utility function, the response of wage to labor productivity is more in line with the empirical characteristics as documented by Pissarides (2009) and Haefkle et al (2013).

Household optimization condition The household optimizes its lifetime utility by choosing its savings options in L_t. By substituting equation (2.4) into equation (2.2), we have

$$C_t+L_t = W_tN_t+b(1-N_t)+r_{k,t}K_t+\pi_t+(1-f_k(\theta_{k,t-1}))(1-\delta_k)L_{t-1}+\psi(1-\delta_k)s_eK_t \tag{2.7}$$

I denote the Lagrange multipler on the household budget equation (2.7) as Λ_t and the multiplier on the liquid asset transition ie equation (2.4) as λ_t. The Lagrangian ($\mathcal{L}$) set up is as follows:

$$\begin{aligned}\mathcal{L} =& E_0 \sum_{t=0}^{\infty} \beta^t \{U\big(C_t, N_t, U_t^o\big) - \Lambda_t \big[\{C_t + L_t - W_tN_t - b(1-N_t)- \\ & r_{k,t}K_t - \pi_t - (1-f_k(\theta_{k,t-1}))(1-\delta_k)L_{t-1} - \psi(1-\delta_k)s_eK_t\}+ \\ & \lambda_t(K_{t+1} - (1-\delta_k)(1-s_e)K_t - (f_k(\theta_{k,t}))L_t)\big]\end{aligned} \tag{2.8}$$

First order condition for C_t gives $\Lambda_t = \beta^t U_c(C_t, N_t, U_t^o)$ and the stochastic discount factor,

$$\Lambda_{t+1|t} = \Lambda_{t+1}/\Lambda_t = \beta U_c(C_{t+1}, N_{t+1}, U_{t+1)}^o)/U_c(C_t, N_t, U_t^o)$$

The first order conditions for L_t and K_{t+1} are as follows:

$$1 = E_t\Lambda_{t+1|t}(1 - f_k(\theta_{k,t}))(1-\delta_k) + f_k(\theta_{k,t})\lambda_t \tag{2.9}$$

$$\lambda_t = E_t\Lambda_{t+1|t}\big[r_{k,t+1} + (1-\delta_k)(1-s_e)\lambda_{t+1} + \psi(1-\delta_k)s_e\big] \tag{2.10}$$

In equation (2.9), the marginal cost of giving up one unit of consumption in equilibrium equals the average return of the shadow value of matched liquid asset and unmatched liquid asset. The shadow value of capital, λ_t is given by (2.10) which returns a continual stream of capital rental return subjected to depreciation and separation. In the event of separation, only a portion is recovered as given by ψ. The return is lower the less the recoverable amount in the event of separation. As usual the transversality condition holds through appropriate calibrations for a solution to the optimization problem.

2.4.3 Representative Firm

The representative firm observes an exogenous technology A_t at the beginning of the period. Given an existing stock of capital, K_t, the firm decides the labor input, N_t to produce output Y_t by posting job vacancies $V_{n,t}$ at the cost of c_n taking the labor market tightness i.e. $\theta_{n,t}$ as given. The firm's production function is a constant returns to scale technology:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha} \tag{2.11}$$

At the end of each period, the firm also decides the capital stock for the next period, K_{t+1}. The firm does this by posting the necessary vacancies, $v_{k,t}$ at the cost of c_k to decide the next period capital holdings taking the market tightness of the physical capital market $\theta_{k,t}$ as given. Hired labor starts production within the period while new capital starts production one period later. The objective function which the firm optimizes every period is the present value of future profit streams discounted by the stochastic discount factor $\Lambda_{t+s|t}$. The value function, V_t, is obtained by choosing the vacancies, $v_{k,t}$ and $v_{n,t}$ to place in each period in the physical capital and labor markets respectively.

$$V(K_t, N_{t-1}) = \max_{\{v_{n,t+s}, v_{k,t+s}\}_{s=0}^{\infty}} Y_t - N_t W_t - \phi_t - r_{k,t} K_t + E_t \Lambda_{t+1|t} V(K_{t+1}, N_t) \tag{2.12}$$

where ϕ_t represents adjustment costs related to labor hiring and the installation of new capital and is given as follows:

$$\phi_t = (c_n/q(\theta_{n,t}) + C_{a,n})h_{n,t} + (c_k/q(\theta_{k,t}))i_t \tag{2.13}$$

In equation (2.13), $h_{n,t}$ is the labor hiring and is equivalent to $q_n(\theta_{n,t})v_{n,t}$. Likewise, firms' investment, i_t is equal to $f_k(\theta_t)L_t = q_k(\theta_{k,t})v_{k,t}$, which is the matching success rate for the firm's vacancies created for the period. The adjustment cost consists of search costs for both labor and capital, $c_n/q(\theta_{n,t})h_{n,t}$ and $(c_k/q(\theta_{k,t}))i_t$ as well as a training and adaptation cost, $C_a,h_{n,t}$ for each new hire. Adaptation cost is not modelled in capital because of the one period ahead installation lead time assumption which includes the cost of installation. The transition equation for the firm's labor stock is subject to job separations δ_n and evolves according to equation (2.14) as follows:

$$N_t = (1 - \delta_n)N_{t-1} + q_n(\theta_{n,t})v_{n,t} \tag{2.14}$$

The capital transition for the firm is as given in equation (2.3) which implies consistency between firms' capital holdings and households' capital holdings that is rented out.

Aggregate Productivity Shocks I restrict the model to only shocks to aggregate productivity, A_t, such that the evolution of aggregate productivity is as follows:

$$\log(A_t) = \rho_a \log(A_{t-1}) + e_{a,t} \tag{2.15}$$

where $e_{a,t}$ is the exogenous shock to productivity in period t and is IID normal across periods and ρ_a is the measure of persistence of the technology shock.

2.4.4 Labor and Physical Market Capital Frictions

Labor Market Contemporaneous hiring in a frictional market in which the hired workers are immediately productive is illustrated in works like Gali (2010) and Blanchard and Gali (2010). I have modelled as such to replicate the spot market mechanism in the RBC model for labor but with matching frictions. This features hiring taking place at the start of the period when the aggregate productivity, A_t is drawn and observed by households and firms.

The labor market frictions is characterized by successful matches produced by a matching function in the form of a Cobb Douglas production function using vacancy postings, $v_{n,t}$ and the number of unemployed workers sent by the household to search for jobs at the beginning of the period, U_t^o as inputs. Accordingly, the matching function is characterized by both constant return to scale and and concavity to each input. The matching function is as follows:

$$M_{n,t} = m_n \left(U_t^o\right)^{\mu_n} \left(v_{n,t}\right)^{1-\mu_n} \tag{2.16}$$

In the above equation, m_n denotes the efficiency of the matching function and μ_n denotes the elasticity of hiring to unemployment and $0 < \mu_n < 1$. The matching function then gives the following identities. When the market tightness is $\theta_{n,t}$ which is defined as $\frac{v_{n,t}}{U_t^o}$ the firm finds a worker with probability, $q_n(\theta_{n,t})$ while the worker faces a job finding probability of $f_n(\theta_{n,t})$. The identities are as follows:

$$q_n(\theta_{n,t}) = m_n \left(\theta_{n,t}\right)^{-\mu_n} \tag{2.17a}$$

$$f_n(\theta_{n,t}) = m_n \left(\theta_{n,t}\right)^{1-\mu_n} \tag{2.17b}$$

Physical Capital Market The households convert consumption goods into physical capital good, one for one costlessly. Physical capital are held by the households with only a portion unmatched, L_t and the remaining matched and rented out to the firms, K_t . Physical capital that is held by the households, L_t, are matched to the firms in a frictional search market characterized by a market tightness of $\theta_{k,t}$. The market tightness, $\theta_{k,t}$, is defined as $\frac{v_{k,t}}{L_t}$ where the denominator is the amount of non-productive asset which participates fully in the search market. The equivalent elasticity of successful matches to unproductive asset that is searching for firms to rent to in the market is given by μ_k where $0 < \mu_k < 1$. The matching function, $M_{k,t}$,and the respective search probabilities of success for firms, $q_k(\theta_{k,t})$ and households,$f_k(\theta_{k,t})$ for the physical capital market are identical to those in the earlier paragraph for labor market namely (2.16), (2.17a) and (2.17b).

$$M_{k,t} = m_k L_t^{\mu_k} \left(v_{k,t}\right)^{1-\mu_k} \tag{2.18}$$

$$q_k(\theta_{k,t}) = m_k \left(\theta_{k,t}\right)^{-\mu_k} \tag{2.19a}$$

$$f_k(\theta_{k,t}) = m_k \left(\theta_{k,t}\right)^{1-\mu_k} \tag{2.19b}$$

2.4.5 Equilibrium Wage

The wage bargaining process follows the simple Nash bargaining rule in most literature. As in Gali (2010) and Blanchard and Gali (2010), the wage is determined by the marginal worker. As in Gali (2010), the outside option for the worker is driven to zero because of the entry of searching workers in the beginning of the period. Waiting for another period would require search costs at the beginning of the next period. The surplus of the marginal worker to the representative household, $S_{w,t}$ is as follows:

$$S_{w,t} = w_t - b - \nu'(N_t) + (1 - \delta_n)E_t\Lambda_{t+1|t}S_{w,t+1} \tag{2.20}$$

The value of the marginal worker to the firm, J_t is as follows:

$$J_t = (1 - \alpha)A_tK_t^{\alpha}N_t^{-\alpha} - w_t + (1 - \delta_n)E_t\Lambda_{t+1|t}J_{t+1} \tag{2.21}$$

The value of a vacancy to the firm, V_t is as follows:

$$V_t = -c_n + q_n(\theta_{n,t})J_t + (1 - q_n(\theta_{n,t}))E_t\Lambda_{t+1|t}V_{t+1} \tag{2.22}$$

Wage Negotiation In recent literature, various wage determination based on microfoundations have been proposed to raise the low volatility of market tightness in a calibrated labor matching models which was first highlighted in Shimer (2005). These schemes involve wage rigidities, Hall (1997) and alternate offers bargaining, Hall and Milgrom (2009). In this paper, I use the standard Nash bargaining mechanism in the canonical DMP model for the marginal worker bargaining and abstract away any wage rigidity assumption except for the rigidity in the replacement rate. I also abstract away intra-firm wage bargaining that is employed frequently in multi-worker firm, Stole and Zwiebel (1996). I follow loosely the same methodology in Blanchard and Gali (2010) in deriving the equilibrium wage, w_t. Under Nash bargaining, firms and households bargain over the total marginal surplus of both the firms and the households, $S_{w,t} + J_t - V_t$. With η as the bargaining strength of the workers, wage is determined as

$$w_t = arg \max_{w_t} S_{w,t}^{\eta}(J_t - V_t)^{1-\eta} \tag{2.23}$$

The outcome of the Nash bargaining is characterized as follows:

$$(1 - \eta)S_{w,t} = \eta(J_t - V_t) \tag{2.24}$$

$$w_t = \eta(1-\alpha)A_t K_t^{\alpha} N_t^{-\alpha} + (1-\eta)(b + \nu_n'(N_t)) \tag{2.25}$$

Free Entry Condition for Labor Matches The assumption of free entry condition (in the absence of fixed overhead) results in the following

$$V_t \leq 0 \tag{2.26}$$

Equation (2.26) holds in equality if vacancies for labor, $v_{n,t} > 0$. Our model does not assume fixed cost overhead for labor matches like Hornstein et al (2007). Models dealing with that introduce an additional impact on the fundamental surplus on the labor matching (see Ljunqvist and Sargent (2015)) to increase the volatility of labor market tightness. Equation (2.26) holding in equality implies

$$J_t = \frac{c_n}{q_n(\theta_{n,t})} + C_{a,n} \tag{2.27}$$

Combining equations (2.27) and (2.21), the transition equation for labor market tightness, $\theta_{n,t}$ is given as follows:

$$\frac{c_n}{q_n(\theta_{n,t})} + C_a, n = (1-\alpha)A_t K_t^{\alpha} N_t^{-\alpha} - w_t + (1-\delta_n) E_t \Lambda_{t+1|t} \left(\frac{c_n}{q_n(\theta_{n,t+1})} + C_a, n\right) \tag{2.28}$$

2.4.6 Equilibrium Capital Compensation

The determination for the rental of capital, $r_{k,t}$, follows the familiar Nash bargain mechanism. When matched, the firm and the household bargain over the price of capital compensation period by period. The value of the match to the household is $V_{k,t}^e$.

$$V_{k,t}^e = r_{k,t} + (1-\delta_k)s_e\psi + (1-\delta_k)(1-s_e)E_t \Lambda_{t+1|t} V_{k,t+1}^e \tag{2.29}$$

The value for an unmatched capital is

$$V_{k,t}^u = 1 - \delta_k \tag{2.30}$$

The surplus of the household from accepting the rental price and leasing out the matched capital is $V_{k,t}^e - V_{k,t}^u$. On the firm's end, the matched capital provides the firm with a stream of marginal capital productivities against which the firm has to pay rental but is subject to separation and depreciation. The value of capital match to the firm, J_t^k, is as follows:

$$J_{k,t} = \alpha A_t K_t^{\alpha-1} N_t^{1-\alpha} - r_{k,t} + (1-\delta_k)(1-s_e)E_t\Lambda_{t+1|t}J_{k,t+1} \tag{2.31}$$

The value of a "vacancy posting for capital" takes into account the cost of the vacancy posting, c^k which is compensated by the probability of success resulting in a match that gives the reward of future marginal revenue stream from the investment net off the payment of capital rental, $r_{k,t}$.

$$V_{k,t}^f = -c_k + q_k(\theta_t^k)E_t\Lambda_{t+1|t}J_{k,t+1} + (1-q_k(\theta_t^k))E_t\Lambda_{t+1|t}V_{k,t+1}^f \tag{2.32}$$

Free Entry Condition for Investment The assumption of free entry condition results in the following

$$V_{k,t}^f \leq 0 \tag{2.33}$$

Equation (2.33) holds in equality if vacancies for capital investment, $V_{k,t} > 0$. Equation (2.33) holding in equality implies

$$E_t\Lambda_{t+1|t}J_{k,t+1} = \frac{c_k}{q_k(\theta_{k,t})} \tag{2.34}$$

$$\frac{c_k}{q_k(\theta_{k,t})} = E_t\Lambda_{t+1|t}\{\alpha A_{t+1}K_{t+1}^{\alpha-1}N_{t+1}^{1-\alpha} - r_{k,t+1} + (1-\delta_k)(1-s_e)\frac{c_k}{q_k(\theta_{k,t+1})}\} \tag{2.35}$$

Capital compensation The determination of compensation embodied in $r_{k,t}$ is similar to the previous section. With η^k as the bargaining strength of the households, $r_{k,t}$ is determined as

$$r_{k,t} = arg\max_{r_{k,t}}(V_{k,t}^e - V_{k,t}^u)^{\eta_k}(J_{k,t} - V_{k,t}^f)^{1-\eta_k} \tag{2.36}$$

The derivation of the $r_{k,t}$ makes use of equations (2.36), (2.29), (2.30), (2.31), (2.32), (2.34) and the FOC equations (2.9) and (2.10). The outcome of the Nash bargaining is characterized as follows:

$$(1-\eta_k)S_{k,t} = J_{k,t} \tag{2.37}$$

$$r_{k,t} = \eta_k\{\alpha A_t K_t^{\alpha-1}N_t^{1-\alpha} + (1-\delta_k)(1-s_e)c_k\theta_{k,t}\} + (1-\eta_k)(1-\psi)(1-\delta_k)s_e \tag{2.38}$$

In equation (2.38), the rental of capital, $r_{k,t}$ increases with both productivity and market tightness which are driven by firm's demand. It also increases with the deadweight loss $(1-\psi)$ from reallocation cost which empirically is acyclical and provides a countervailing force to the cyclical effect from market tightness and productivity effect. As my focus is not on reallocation effects and cost, I held these as constant.

2.5 Labor Search Decision

The labor participation decision is determined by marginal disutility from search activity and the rewards from the search activity in the form of the probability of a successful match. The FOC equation is given as:

$$\nu_u'(U_t^o) = f_n(\theta_{n,t}) S_t^w U_c(C_t, N_t, U_t^o) \tag{2.39}$$

The labor force participation rate is given as follows:

$$F_t = N_t + U_t \tag{2.40}$$

I use a simple formulation for the utility functions, $\nu_u(U_t^o)$ and $\nu_n(N_t)$:

$$\nu_u(U_t^o) = \frac{\chi_u (U_t^o)^{1+\phi_u}}{1+\phi_u} \tag{2.41}$$

$$\nu_n(N_t) = \frac{\chi (N_t)^{1+\phi_n}}{1+\phi_n} \tag{2.42}$$

2.6 Closing the model

Market clearing conditions for goods market gives:

$$C_t + c_k v_{k,t} + c_n v_{n,t} + C_{a,n} q(\theta_{n,t}) v_{n,t} + Inv_t = A_t K_t^{\alpha} N_t^{1-\alpha} \tag{2.43}$$

2.7 Calibration

Household I set the discount factor, β to 0.99 to reflect the annual interest rate of 4%. For household preferences, I set $\sigma = 1$ which is represents an intertemporal elasticicy of substitution of 1.

Labor market The steady state job finding rate is set to 0.7 as the standard setting for steady state quarterly job finding rate (see Blanchard and Gali (2010)). Drawing upon the works of Hagedorn and Manovski(2008) and earlier evidence by Silva and Toledo (2009), I take the average cost of hiring a worker to be 4% of the quarterly wage ie $\frac{c_n}{q_n(\theta_n)} = 0.04\bar{W}$ in steady state. The elasticity of the matching function to unemployment, μ_n is set to be 0.5 is in line with calibration in the literature as according to Petrongolo and Pissarides(2005) and argued by Nagypal and Mortensen(2007). I set the wage bargain share for workers, $\eta_n = 0.5$ as implied by the Hosios condition. The replacement rate for the US is between 0.4 x steady state wage rate i.e. $\bar{W}$ as argued by Nagypal and Mortensen (2007). I apportion it reflecting both UI and social welfare at 0.1 $\bar{W}$ and the remaining 0.3 to fixed costs of work. The steadystate level of disutility to work ψN^{ϕ_n} is set to 0.5 of marginal product of labor along the line suggested Nagypal and Mortensen(2007) and Hall(2003). The implied adjustment cost from the steady state conditions implosed on the model is $0.325\bar{W}$ which is in line with empirical studies on adaptation costs and training costs for labor (see Sakellaris(2000)).

I set the steady state unemployment rate to 5% in line with the long run unemployment rate of the US economy (see Gali (2010)). I set exogenous separation of job matches to 12% as in Blanchard and Gali (2010) which draws upon the works of Hall (1995) and Davis et al (1996). The steady state labor force participation rate is targetted at 0.63.

Firms I set the persistence of aggregate technology shocks, ρ_a as 0.975 and standard deviation, σ_a as 0.0072(King and Rebelo, 1999). I set α to 1/3 such that $1 - \alpha$ reflects the labor share of income.

Physical Capital Market I draw upon the works of Ramey and Shapiro (1999) which reported that 71% of capital separation consists of retirements with the remaining from exits or sales. Depreciation of capital stock is calibrated in line with RBC literature targets of 0.025 quarterly or the equivalent of 10% per annum. The exogenous separation rate of capital matches is then calibrated as 0.01. The steady state capital matching rate, I target $f_k(\theta_k)$ at 0.5 which is in line with long run average of sales to inventory for finished durable goods. The capital matching rates for different capital goods range from very liquid machineries and capital goods at 0.86 to very illiquid of 0.2 for plant and building. In Kurmann and Petrosky-Nadeau (2007), the authors targeted the midpoint of 0.5 which also corresponds to the long run average of sales to inventory for finished durable goods. I set the search cost $c_k/q_k(\theta_k)$ to be 0.59 of the rental rate as implied by the steady state equations for the rest of the calibration with quarterly steady state return on capital of 3.7%. This represents a search cost of less than 2 months of rental costs. I set the bargaining strength of the households, η_k to be 0.7 and the elasticity of match to liquid capital on the search market, μ_k to be 0.7 in line with the estimated value in Ottonello (2015) of 0.8 and the calibration in Kurmann and Petrosky-Nadeau(2007) of 0.5. The bargain strength is set to imply Hosios conditions given the lack of empirical evidence.

2.8 Loglinearized Model

I present the loglinearized model and denote all small caps variable as the deviation of log variable from its steady state ie $k = logK_t - log\bar{K}$. There are variables like λ for which there is no small caps, the representation $\hat{\lambda}$ then represent the same deviation of log of the variable from its steady state log value.

Capital transition equation (2.3)

$$k = (1-\delta_k)(1-s_e)k(-1) + (1-(1-\delta_k)(1-s_e))\{(1-\mu_k)\theta_k + l\} \tag{2.44}$$

Liquid asset transition equation (2.4)

$$\begin{aligned} l &= (1-\bar{f}_k)(1-\delta_k)l(-1) - \bar{f}_k(1-\delta_k)(1-\mu_k)\theta_k + inv(I\bar{n}v/\bar{L}) \\ &+ \psi(1-\delta_k)s_e(\bar{K}/\bar{L})k(-1) \end{aligned} \tag{2.45}$$

Labor transition equation (2.14)

$$n = (1-\delta_n)n(-1) + (1-(1-\delta_n))\{(1-\mu_n)\theta_n + u^o\} \tag{2.46}$$

Household investment optimization (2.9) and (2.10)

$$0 = E_t\beta(1-\bar{f}_k)(1-\delta_k)\{m - m(+1) - \bar{f}_k/(1-\bar{f}_k)(1-\mu_k)\theta_k\}$$
$$+ (1-\beta(1-\bar{f}_k)(1-\delta_k))\{(1-\mu_k)\theta_k + \hat{\lambda}(+1)\} \tag{2.47}$$
$$\hat{\lambda} = E_t(m - m(+1)) + E_t\beta(\bar{r_k}/\bar{\lambda})r_k(+1) + \beta(1-\delta_k)(1-s_e)E_t\hat{\lambda}(+1) \tag{2.48}$$

Aggregate Productivity Shock equation (2.58)

$$a = \rho_a a(-1) + e_a \tag{2.49}$$

Equilibrium Wage equation (2.25)

$$w = \eta_n(1-\alpha)\frac{Y}{WN}(a + \alpha k(-1) - \alpha n)$$
$$+ (1-\eta_n)\frac{\overline{\chi N^{\phi_n}}}{W}\phi_n n \tag{2.50}$$

Free entry condition for labor match

$$\mu_n\theta_n = (1-\alpha)\frac{\bar{q_n}Y}{c_n N}(a + \alpha k(-1) - \alpha n) - \frac{W}{c_n/(\bar{q_n})}w$$
$$+ (1-\delta_n)\beta\{\mu_n\theta_n(+1) - (m(+1) - m)\} \tag{2.51}$$

Equilibrium capital rental rate

$$r_k = \eta_k\alpha Y/\bar{r}_k K(a + (\alpha-1)k(-1) + (1-\alpha)n) + \eta_k(1-\delta_k)(1-s_e)c_k\bar{\theta_k}/\bar{r}_k\theta_k \tag{2.52}$$

Free entry condition for capital matches

$$\mu_k\theta_k = E_t\{-\sigma(c(+1) - c) + \beta\alpha\frac{\bar{q_k}Y}{c_k K}(a(+1) + (\alpha-1)k + (1-\alpha)n(+1))$$
$$- \beta\frac{\bar{r_k}}{c_k/(\bar{q_k})}r_k(+1) + (1-\delta_k)(1-s_e)\beta\mu_k\theta_k(+1)\} \tag{2.53}$$

Goods Market Clearing equation (2.43)

$$C/Yc + (\bar{Inv}/Y)inv + (c_k V_k/Y)v_k + (C_a\bar{H}/Y)h + (c_n V_n/Y)v_n$$
$$= a + \alpha k(-1) + (1-\alpha)n \tag{2.54}$$

Discount factor m

$$m = -\sigma(\bar{C}c - \overline{\frac{\chi N^{1+\phi_n}}{(1+\phi_n)}}(1+\phi_n)n)/\bar{M} \tag{2.55}$$

Labor force participation equation

$$f = N/Fn + U/Fu \tag{2.56}$$

FOC for labor search

$$\phi_u u^o = (1 - mu_n)\theta_n + \frac{c_n}{q(\theta_n)}/(\frac{c_n}{q(\theta_n)} + C_a)\mu_n\theta_n + m \tag{2.57}$$

2.9 Evaluation of Model Performance

In this section, I examine the central prediction of the model of the artificial economy in particular the standard deviations of key variables with the empirical behavior of the US economy and the behavior of a standard RBC model. Table 2.1 shows the standard deviations of the key variables while Table 2.2 shows the correlation between the variables.

Standard Deviations	Data	Benchmark RBC Model	Frictional Model
Output	1.62	1.17	1.52
Consumption	0.94	0.53	0.85
Employment rate,N	1.52	0.34	0.92
Investment	4.39	3.12	2.52
Inventory to sales	0.89	-	0.83
Labor force part.	0.48	-	0.6

Table 2.1: Performance of Key Variables

The model shows strong volatility in the labor market. The labor market volatility results in a more volatile consumption, output and labor that is more in line with the empirical data than the RBC model. However, the performance of the model for investment is worse in spite of the availability of unused and unmatched capital available. The lack of an amplification effect of the unused capital has also been reported in Kurmann and Petrosky-Nadeau (2007) and Ottonello (2015). The model also shows a sales to inventory ratio volatility for capital goods that is

Correlations (to Output)	Data	Frictional Model
Consumption	0.69	0.98
Employment(N)	0.87	0.98
Investment	0.87	0.98
Inventory to sales ratio(Capital)	-0.70	-0.97
Labor force part.	0.3	0.8

TABLE 2.2: Correlations of Aggregate Variables and Y

Standard Deviations $(\sigma(.)/\sigma(\frac{Y}{N})$	Data	Frictional Model
Real Wage	0.67	0.89
Unemployment	6.9	11.95
Vacancy	8.27	15.23
Tightness	14.96	13.3
Job Finding Rate	5.9	7.9

TABLE 2.3: Labor Market Characteristics

	u	v	θ_n	Job find. rate	y/n
u	1	-0.894	-0.971	-0.949	-0.408
v	-	1	0.975	0.897	0.364
θ_n	-	-	1	0.948	0.396
Job find. rate	-	-	-	1	0.396
y/n	-	-	-	-	1

TABLE 2.4: Cross correlations - Quarterly US labor market - HKV(2007)

	u	v	θ_n	Job find. rate	y/n
u	1	-0.99	-0.99	-0.99	-0.7
v	-	1	0.99	0.99	0.62
θ_n	-	-	1	1	0.62
Job find. rate	-	-	-	1	0.62
y/n	-	-	-	-	1

TABLE 2.5: Cross correlations - Benchmark model

in line with the empirical data on finished durable goods and structures. The labor market volatility is achieved while reconciling the 2 key factors which are as follows:

Wage Elasticity The wage elasticity to labor productivity from the benchmark model is 0.98*0.89 = 0.87. The high wage elasticity differs from the wage rigidity strategy often used in literature to magnify the volatility of the labor market. This is of interest in the context of Pissarides (2009) and Haefke, Sonntag and van Rens (2013). In Pissarides (2009), Pissarides argued for the flexibility of wage for new hires with the wage elasticity for new hires close to 1. Haefke, Sonntag and van Rens (2013) estimated that the elasticity of wages to productivity should be close to 1 and above 0.80.

Volatility and Procyclicality of the Disutility of Labor In the model, the level of labor disutility that plays an important role in the wage formulation, is set to 0.51 X marginal labor product. This is in line with the calibrations in the literature based on estimates from Hall (2000) - (see Nagypal and Mortensen (2007) and Chodorow-Reich and Karabarbounis (2016)). However, in the literature, the labor disutility is also set to a constant level to increase the volatility of the tightness of the labor market. Chodorow-Reich and Karabarbounis (2016) argues that the component of the opportunity cost of work that is not procyclical which is the effective social security payout is only around 6% although it is countercyclical. The disutility of labor on the other hand, is highly volatile and procyclical under a power utility function formulation and it contributes to at least 50% of the opportunity cost of labor. In the model here, the standard deviation of the labor disutility is 1.4 X the standard deviation of the marginal labor product. It is also highly procyclical with a correlation of 0.98 with Y. The model here still features a fixed component for a fixed cost of employment that is calibrated at around 0.3 X marginal labor product. This is along the line of calibration that Chodorow-Reich and Karabarbounis (2016) used in the calibration for a Hagedorn and Manovski model in their paper. Further, a sensitivity test is performed by lowering the fixed cost to 0.2 X marginal labor product and raising the disutility of labor to 0.61. The wage is now more volatile at 0.93 and u, v and θ_n are reduced but does not change the results that a highly volatile labor market can be achieved even though the opportunity cost of work is highly procyclical and volatile. The results are as presented in Table 2.6:

Lack of amplification for investment The volatility of investment does not increase with the amplification inspite of the amplification from employment. The relative standard deviation with respect to output for investment spending by the firms decreases to 1.68. The relative amount of investment goods that is

Standard Deviations ($\sigma(.)/\sigma(\frac{Y}{N})$	Data	Frictional Model
Real Wage	0.67	0.93
Unemployment	6.9	10.06
Vacancy	8.27	12.4
Tightness	14.96	11.89
Job Finding Rate	5.9	7.0

Table 2.6: Labor Market Char. : fixed cost = 0.2 marg. lab. prod.

produced(including unsold inventory) = 0.35/0.152 = 2.32. Both measures are below the RBC model in relative terms. This is depite the model demonstrating inventory behavior that is in line with empirical behavior of inventory to sales ratio for durable consumption goods.

2.10 News Shocks and Pigou Cycles

In the sections that follow, I augment the productivity shocks with news shocks about future technology shocks. This experimentation allows us to assess the impact of the amplification mechanism of the model that comes from the availability of the pool of unused resources for production when the current production is not yet affected by the productivity improvements that only occurs in the future.

Definition of Pigou Cycle As defined in denHaan and Kaltenbrunner(2009), in a Pigou Cycle, the economy expands in consumption, labor and capital investment in anticipation of an increase in future productivity. However in most models, capital is modeled with a one period ahead install time and is therefore predetermined. Likewise, if the model features one period ahead hiring, labor is also predetermined. With these two constraints, either consumption or investment goods can increase but not both as the production capacity is constrained. In addition, even with a model that features contemporaneous hiring and production in the same period, the income effect on labor supply (see (Krusell and Mckay (2010)) constrains the increase in labor employment in the economy and hence the available output.

Beaudry and Portier (2014) reviews the difficulty in the modeling of a structural RBC model in which consumption, employment and investment rise together in response to news about future shocks. Christiano et al (2008) demonstrates a RBC model with internal habit formation, investment adjustment costs and variable capital utilization. In that model, consumption, employment and investment rises marginally. To create a boom-bust scenario, the authors augmented the model with price rigidity and an accomodative monetary policy so that the effect is magnified.

The model evaluation which is performed here is similar to the exercise done in denHaan and Kaltenbrunner (2009). denHaan and Kaltenbrunner(2009) modeled an RBC model with contemporaneous hiring, endogenous labor force participation and new capital investment with each new job match as well as capital adjustment in the existing matches with news shocks. However, as reported by the authors, the model can only generate Pigou Cycle on a narrow range of values for the calibration of the intertemporal elasticity of substituion and furthermore the range is below 2, which is generally outside the normal range of calibration in the literature.

News Shocks To study news shocks, the model is modified for both surprise and news shocks to aggregate productivity, A_t, such that the evolution of aggregate productivity is as follows:

$$\log(A_t) = \rho_a \log(A_{t-1}) + e_{a,t} + e_{n,t-4} \tag{2.58}$$

News shock is represented by $e_{n,t-4}$ which represents an expectation shock occurring in period 0 about a future shock that occurs in period 4. The characteristics of $e_{n,t-4}$ is the same as $e_{a,t}$ i.e. IID normal with $\sigma(e_{n,t}) = 0.0075$ and mean 0.

2.11 Results - News Shocks

The impulse response functions of the benchmark model in response to surprise shocks are as shown in Figures 2.1 panels 1 to 3 while the impulse response to the expected shock are documented in Figures 2.2 panels 1 and 2. As shown in Figure 2.2, the calibrated model is not able to generate an increase in investment expenditure by firms except in the period before the shock and it is not significant. The consumption smoothing effect results in the increase in consumption at the expense of investment spending by the households. Inventory also decreases because less investment goods are produced. This is despite the increase in labor matches created.

Alternate Calibrations The model is re-calibrated in an exercise to investigate the directions in which the model performance could be augmented. I conduct the same experimentation as in denHaan and Kaltibrunner (2009). I increase the elasticity of intertemporal substitution in steps from 1.0 to 2.0 and additionally targetted the steady state household's matching rate of the capital market from 0.5 to 0.3.

The re-calibrations for the intertemporal elasticity of substitution are along the same line as the calibration exercise in denHaan and Kaltibrunner (2009). The calibration values are not standard calibration values in macroeconomic models. However, Thimme (2017)'s survey of the calibrations for the intertemporal elasticity of substitution suggests that the calibration values for IES (intertemporal elasticity of substitution) between 1.5 and 2 are plausible values especially in heterogeneous settings where wealth and capital holdings are concentrated in a small section of the population. In micro-studies, the estimation of IES of 2.5 or above 2 have been proposed taking into account of the limited particpation of stockholdings (see Attanasio (2002) and Vissing-Jorgensen (2002)).

Our second recalibration exercise is to target the sales to stock ratio of capital goods. While the long run sales to stock ratio for durable final goods implies a finding rate of 0.5, the long run sales to stock ratio for structures, plants and fixed assets is around 0.4. A calibration exercise towards values ranging from 0.4 to 0.3 would be consistent with structures and fixed assets equipment that are less "liquid", take for example aircrafts and plant machineries.

I present the impulse response functions for the calibrations of (F_k, σ) of (0.5,0.6),(0.4,0.7) and (0.3,0.8). These calibrations results in positive growth in consumption, investment, output and labor. I will discuss the analysis in the next section. The reported response functions are not singular readings but sample readings in a range of calibration values. A calibration target of F_k of 0.5 results in a very narrow range of 0.55$< \sigma <$0.6 that can generate Pigou Cycles. The table of calibrations for F_k and σ that can generate Pigou Cycles is given in Table 2.1:

F_k	σ lower value	σ higher value
0.5	0.55	0.6
0.4	0.6	0.7
0.3	0.65	0.9

TABLE 2.1: Calibrations Generating Pigou Cycles - in steps of 0.05

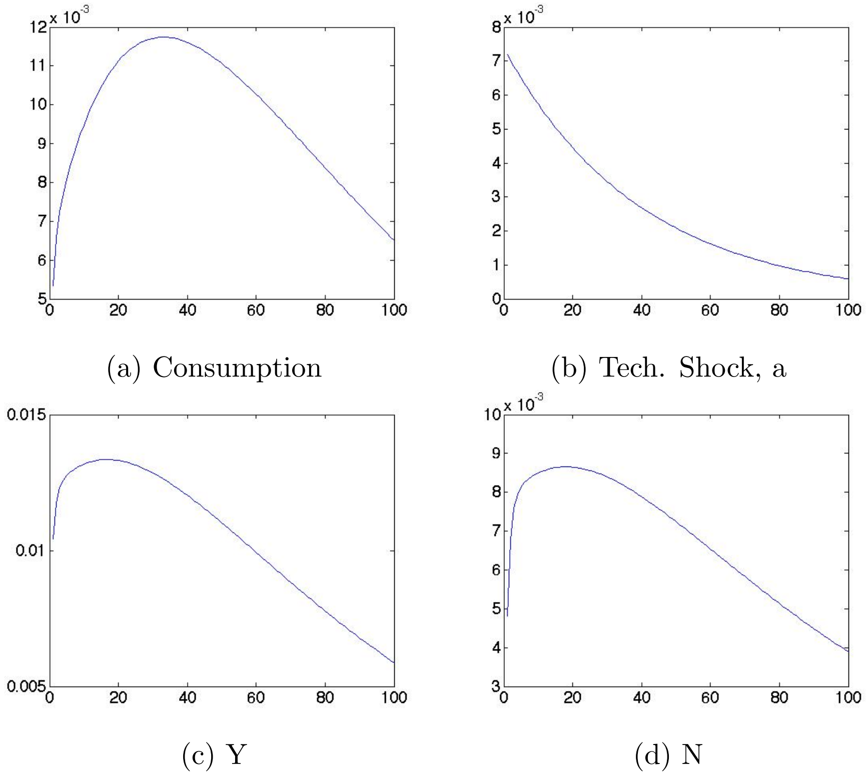
2.11.1 Discussions

While the calibrations show that there are plausible values that can generate Pigou Cycles, we note that the magnitude of investment expenditures generated are not nearly as strong even with an IES that is calibrated above 1. This has to do with the lack of amplification from a physical matching market. While the labor market is volatile and supplies the amplification needed to drive the needed production to support the consumption growth, the capital market movement is quite restricted. Another finding is that with lower calibrated sales to stock ratio representing more illiquidity in the physical capital market, the range for IES increases and extends closer to 1, the standard calibration for IES.

2.12 Conclusions

The model could be best described in two parts. First a frictional model incorporating frictional labor and physical capital markets is developed. The issue of a labor market lacking in volatility is eliminated by the incorporation of a sunk fixed costs for labor match formation and an endogenous labor supply so that the outside option feedback mechanism from the labor market is eliminated. The outcome is that a wage that is highly elastic and the opportunity cost of work that is highly volatile and procyclical are both left intact while the responsiveness of the labor market to shocks is greatly augmented. The capital market exhibits the same issues as in the generic model of the labor market and this is exhibited in the low responsiveness of investment to shocks. However the inventory characteristics are in line with the literature on inventories of durable goods. This area could be an area of future investigation.

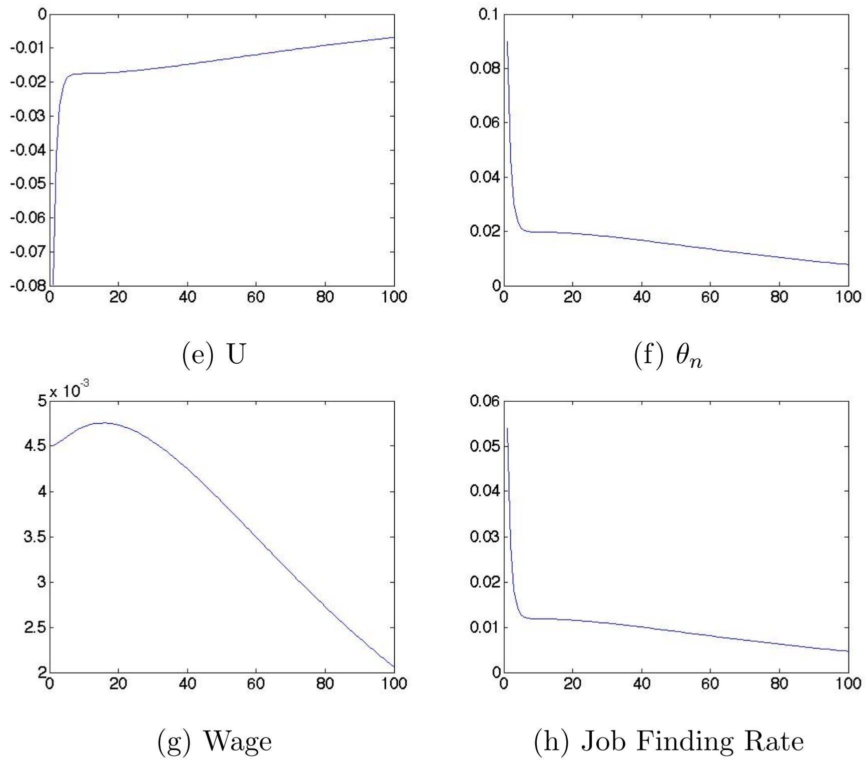
The model is put through a test with news shock. It achieves the objective of generating Pigou Cycle features with a higher calibration value for the intertemporal elasticity of substitution and a physical capital market with a lower liquidity that is more consistent with that of structures and fixed assets. However, the main mechanism is through the increase in responsiveness of the labor market. The matching frictions in the physical capital market only serves a secondary channel in offsetting the decline in the production of investment goods which is channeled away into consumption goods. Future research can proceed along the line of amplification mechanisms on capital investment. Given the installation lead time for capital featured in the model, it is likely that the magnification will come from capital work week adjustment or variable capital utilization that has been studied quite extensively. Several additional approaches can also be applied and has been demonstrated in works by Christiano et al (2010) and denHaan and Lozej(2010). The earlier paper features nominal price rigidity and accomodative monetary policies to magnify the Pigou Cycle effects. These mechanisms should be seen as complementary and not competing explanations.



(a) Consumption (b) Tech. Shock, a

(c) Y (d) N

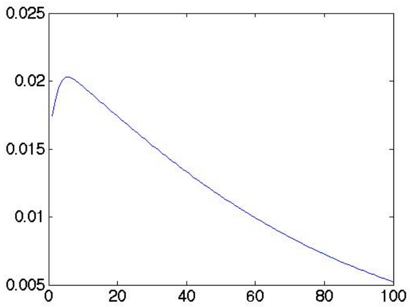
FIGURE 2.1: Panel 1 -Impulse Resp. to Unanticipated Tech. Shock



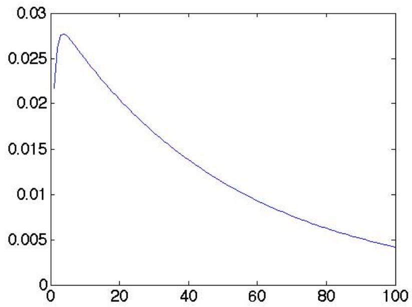
(e) U (f) θ_n

(g) Wage (h) Job Finding Rate

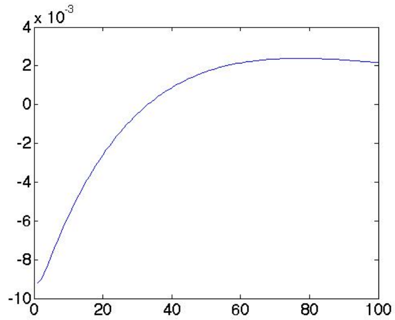
FIGURE 2.1: Continued Panel 2 - Impulse Resp. to Unanticipated Tech. Shock



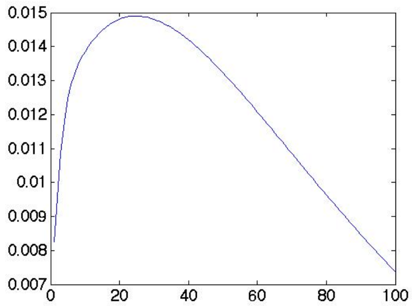
(i) Investment Expenditure



(j) Investment Goods Produced

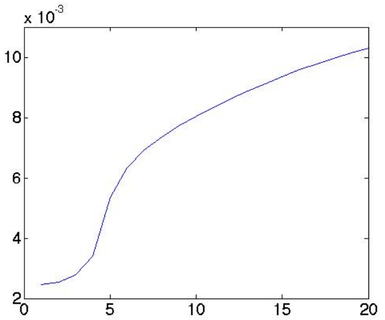


(k) Stock to Sales Ratio

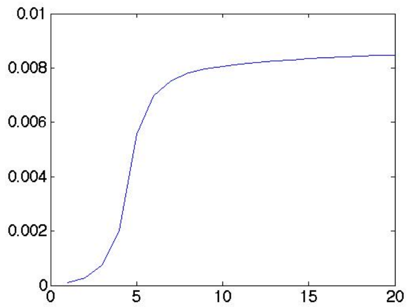


(l) Inventory

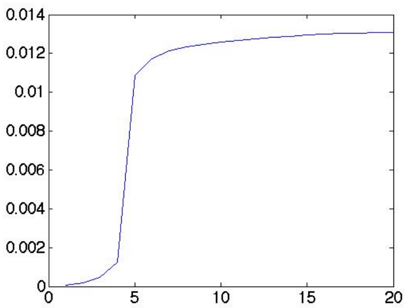
FIGURE 2.1: Continued Panel 3 -Impulse Resp. to Unanticipated Tech. Shock



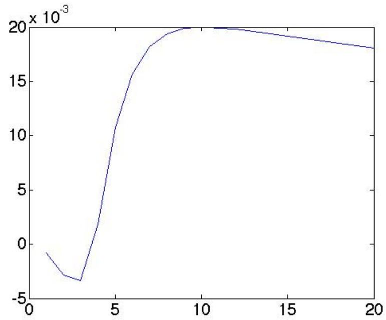
(a) Consumption



(b) N

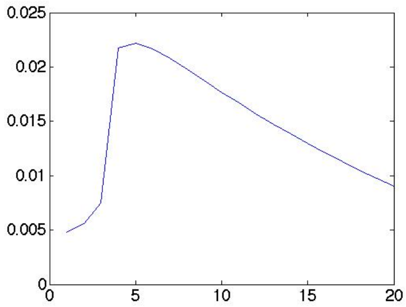


(c) Y

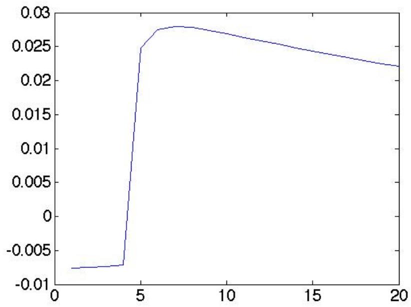


(d) Invest. Expenditure

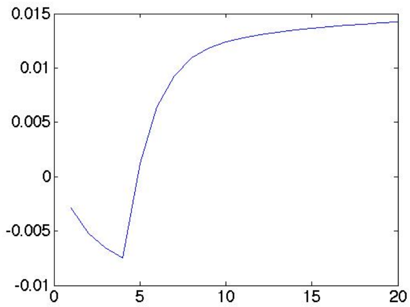
FIGURE 2.2: Panel 1 -Impulse Resp. to Anticipated Tech. Shock in Period 5-Benchmark Model



(e) Jk-Value of Capital to Firms

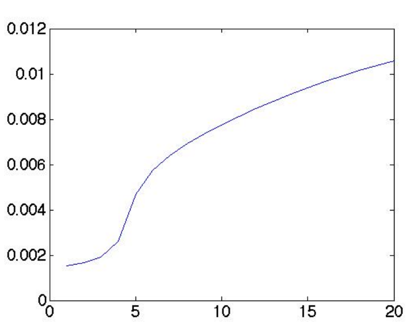


(f) Invest. Goods Produced

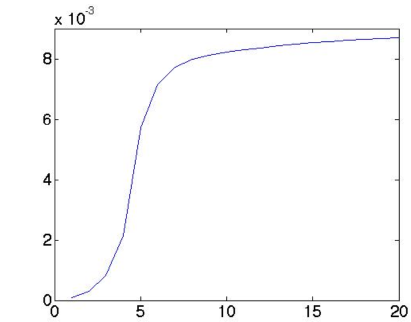


(g) Inventory of Unmatched Capital

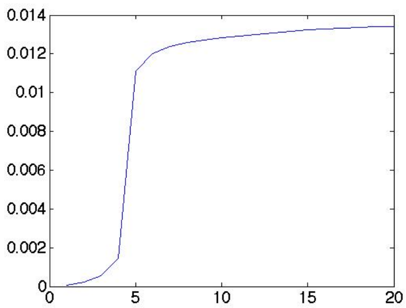
Figure 2.2: Continued Panel 2 - Impulse Resp. to Anticipated Tech. Shock - Benchmark Model



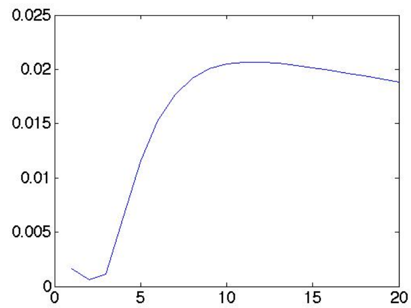
(a) Consumption



(b) N

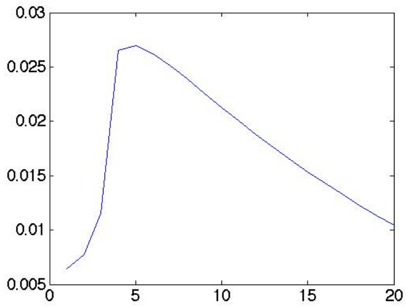


(c) Y

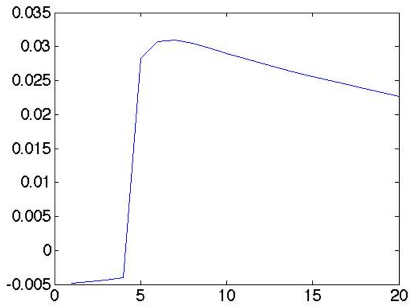


(d) Invest. Expenditure

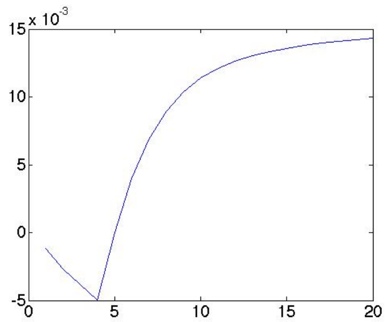
Figure 2.3: Panel 1 -Impulse Resp. to Anticipated Tech. Shock $\sigma = 0.8$ $F_k = 0.3$



(e) Jk-Value of Capital to Firms

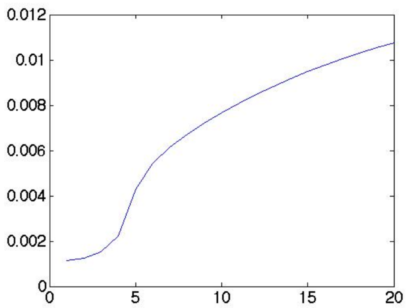


(f) Invest. Goods Produced

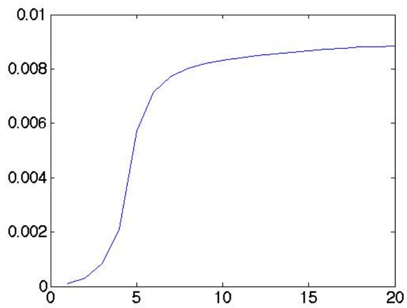


(g) Inventory of Unmatched Capital

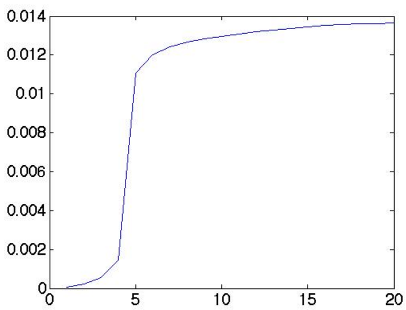
FIGURE 2.3: Continued Panel 2 - Impulse Resp. to Anticipated Tech Shock- $\sigma = 0.8$ $F_k = 0.3$



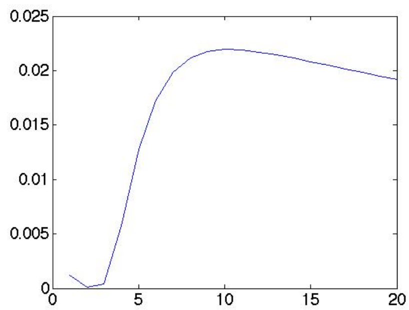
(a) Consumption



(b) N

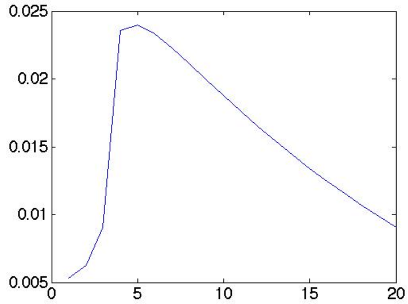


(c) Y

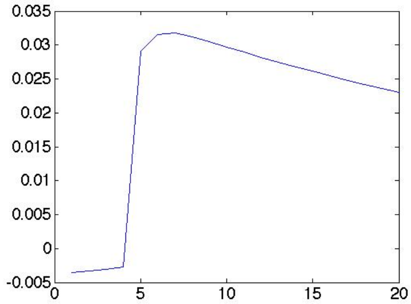


(d) Invest. Expenditure

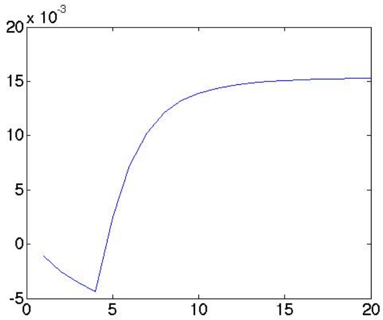
FIGURE 2.4: Panel 1 -Impulse Resp. to Anticipated Tech. Shock- $\sigma = 0.7$ $F_k = 0.4$



(e) Jk-Value of Capital to Firms

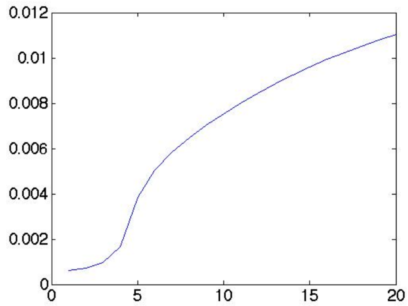


(f) Invest. Goods Produced

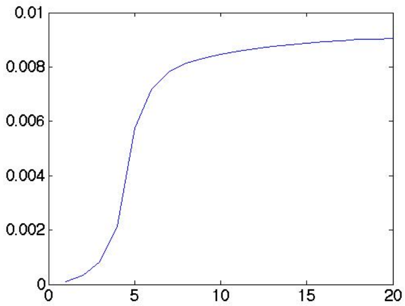


(g) Inventory of Unmatched Capital

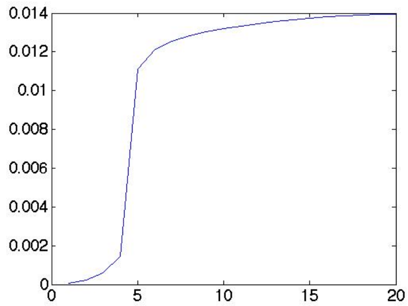
Figure 2.4: Continued Panel 2 - Impulse Resp. to Anticipated Tech. Shock- $\sigma = 0.7$ $F_k = 0.4$



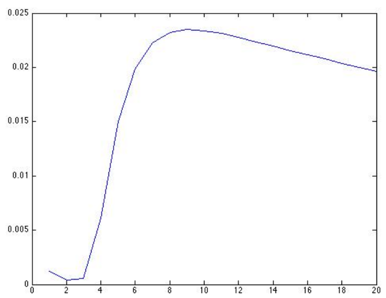
(a) Consumption



(b) N

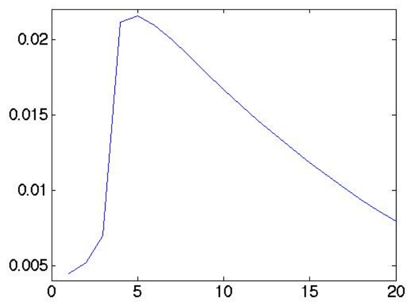


(c) Y

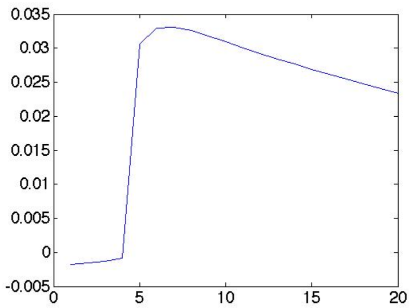


(d) Invest. Expenditure

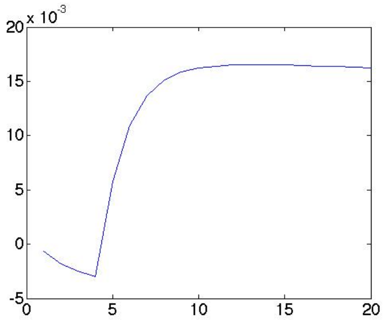
Figure 2.5: Panel 1 -Impulse Resp. to Anticipated Tech Shock- $\sigma = 0.6$ $F_k = 0.5$



(e) Jk-Value of Capital to Firms



(f) Invest. Goods Produced



(g) Inventory of Unmatched Capital

FIGURE 2.5: Continued Panel 2 - Impulse Resp. to Anticipated Tech. Shock- $\sigma = 0.6$ $F_k = 0.5$

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