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Product Cycles and Prices: Search Foundation*

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Abstract

This paper develops a price model with a search foundation based on product cycles and prices. Observations conclude that firms match with a new product, then set a new price through negotiation and fix the price until the product exits from a market. This evident behavior results in a new model of price stickiness as a Search-based Phillips curve. The model includes a New Keynesian Phillips curve with Calvo's price adjustment as a special case and describes new phenomena. First, new parameters and variables of a frictional goods market determine price dynamics. As separation rate in a goods market decreases, price becomes more sticky, i.e., a flatter slope in a Search-based Phillips curve, since the product turnover cycle is sluggish. Moreover, other goods market features, such as probability of match, elasticity of match, and bargaining power for a price setting decide price dynamics. Second, goods market friction can make endogenously persistent inflation dynamics without an assumption of indexation to a lagged inflation rate. Third, when the number of a product persistently increases, deflation continues for a long period. It can explain a secular deflation.

Keywords: Phillips curve; search and matching; product chain

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1 Introduction

> "We have all visited several stores to check prices and/or to find the right item or the right size. Similarly, it can take time and effort for a worker to find a suitable job with suitable pay and for employers to receive and evaluate applications for job openings. Search theory explores the workings of markets once facts such as these are incorporated into the analysis. Adequate analysis of market frictions needs to consider how reactions to frictions change the overall economic environment: not only do frictions change incentives for buyers and sellers, but the responses to the changed incentives also alter the economic environment for all the participants in the market. Because of these feedback effects, seemingly small frictions can have large effects on outcomes."
>
> Peter Diamond

> "Price dynamics in imperfectly competitive markets result from the interplay of sellers' and buyers' strategies. Understanding the microeconomic determinants of price setting and their welfare or macroeconomic implication - such as the role of friction in monopolistic competition or the effects of inflation - therefore requires an analysis which incorporates the decision problems of both types agents. With this in mind, this paper brings together two hitherto separated, but highly complementary, strands of the imperfect competition literature, namely optimal price adjustment and search model."
>
> Roland Benabou

Recent observations from microdata reveals facts for product cycles and prices. We have revealed a new simple reason for price stickiness. Firms match with new products, then set new prices with negotiation and fix prices until the product exits from a market.

Broda and Weinstein (2010) show that using the universe of products data including wholesales and retail goods, product turnover rate in the United States is about 25 percent annually for product entry and exit and these product cycles have a significant effect on a price index. Nakamura and Steinsson (2012) sheds light on product turn over being a key mechanism for price change, a discussion of so called product replacement bias. They show that 40 percent of products are replaced without price change and 70 percent are replaced with two or less price changes after the introductions of goods into markets in raw microdata for trade price indexes. Ueda, Watanabe, and Watanabe (2016) confirm the same facts for Japan using the point of sale scanner data including retail goods. They reveal that a product turnover rate is 30 percent annually. Price adjustment occurs in timing of product turnover and more than half of products do not experience price changes until their exit from the market. These facts indicate that a product cycle and fixed price after entry make price stickiness in several stages from upstream to downstream of a product chain.[1]

On the other hand, to capture price stickiness, a large number of papers for the New Keynesian Phillips Curve assume the Calvo (1983) - Yun (1996) price adjustment in which firms optimally change prices with a certain probability. Their price adjustment mechanism provides a useful proxy for price stickiness. Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007) show that this New Keynesian Phillips Curve based on Calvo (1983) - Yun (1996) price adjustment fits data well. Thanks to tractability capturing a distortion of price dispersion, optimal monetary policy analysis starts with the New Keynesian Phillips Curve with Calvo (1983) - Yun (1996) price adjustment as shown in Woodford (2003). Those analyses justify a key feature of monetary policy in the last few decades, i.e., inflation stabilization as an optimal criteria for monetary policy. However, it is a problem of Calvo (1983) - Yun (1996) price adjustment that does not explicitly express any concrete explanation for price stickiness. Thus, a New Keynesian Phillips Curve can show a different form and implications for monetary policy when we introduce a specific situation regarding price stickiness.

There are several studies to replace the New Keynesian Phillips Curve with the Calvo (1983) - Yun (1996) price adjustment by alternative price models with explicit mechanisms for price stickiness. Mankiw and Reis (2002) build up a sticky-information model. They assume that information diffusion is slow and information updating makes it costly to reset the goods price. In contrast to a New Keynesian model, a sticky-information model includes an infinite sum of expectation for a present inflation rate that has a sufficient persistence of an inflation rate. Gertler and Leahy (2008) develop a tractable state dependent Phillips curve in contrast to a time dependent Phillips curve

[1] Cavallo, Neiman, and Rigobon (2014) show that most products do not change their prices in their lifetime using online price data after first prices in markets.

based on the Calvo mechanism. They assume that firms being in a state to get benefit over cost optimally reset a new price. This Phillips curve with an Ss foundation has the same form as the New Keynesian Phillips Curve. Only a difference between two Phillips curves is a larger response to demand reflecting greater flexibility of price adjustment in the Phillips curve with an Ss foundation.[2]

In sharply contrast to these studies, we propose a new alternative for a model of price stickiness following new observations in micro data. This paper explicitly sets up the situation of infrequent price adjustment using a search and matching procedure. Firms newly match with demand and supply of new products in the goods market and they negotiate the price of a new goods. Firms matched from a previous period with old goods do not change price following the spirit of Shimer (2004) and Hall (2005) in a labor market on a basis of the search theory of Mortensen and Pissarides (1994). This infrequent price adjustment shows a Search-based Phillips curve.

There are several studies for a search and matching in a goods market. Michaillat and Saez (2015) assume a search and matching in a goods market. They show that productive capacity is idle in the U.S. and such no full operating rate implies that sellers have a search friction to find buyers. They match a model to data and show that a fixed-price model describes the data better than a flexible price model does. In terms of trade, Drozd and Nosal (2012) introduce a search and matching into goods trade between countries in a model to solve puzzles regarding the correlation of real export and import prices and the volatility of the real exchange rate. Eaton, Jinkins, Tybout, and Xu (2016) assume a search and matching process for international buyer-seller connections for goods to explain various empirical issues. These papers imply the validity of search and matching for a goods market.

Empirical studies, such as Barrot and Sauvagnat (2016), show that there exist search and matching frictions in production networks using firm level data. They find that the occurrence of natural disasters on suppliers reduces output to their customers when

[2] Also, Woodford (2009) shows a similarity and difference between a state dependent pricing model and a time dependent pricing model under limited information.

these suppliers produce specific input goods and justify that specific input goods are not traded in a centralized market that does not need search frictions. Carvalho, Nirei, Saito, and Tahbaz-Salehi (2016) also show that individual firms can not quickly find suitable alternatives under a decentralized goods market with search friction when firms are faced with a supply-chain disruption by a natural disaster in Japan. They also show that a disruption of the micro supply chain is a key driver of macro aggregated fluctuations.

Our paper is also related to other former studies as follows. In terms of a role of the number of goods on price dynamics, our paper is related to Bilbiie, Ghironi, and Melitz (2012) that assume endogenous producer entry and product creation. They, however, introduce a sticky price by a price adjustment cost of Rotemberg (1982) and derive a Phillips curve including an adjustment cost parameter and the number of goods in a market. The mechanism for price stickiness is sharply contrast to one in our paper. Moreover, a price adjustment is independent from search friction in a goods market. In an application to introduce a Search-based Phillips curve into a general equilibrium model, our paper is related to Kuester (2010) that introduces a search and matching in a labor market and Nash bargaining for a goods price and wage between a household and firms in a framework of Trigari (2009) and Monacelli, Perotti, and Trigari (2010). Kuester (2010), however, assumes a sticky price by the Calvo (1983) - Yun (1996) price adjustment and derives a Phillips curve including a separation rate in a labor market, Calvo parameter, and the number of matched workers. Our paper assumes a search and matching in a goods market and is clearly apart from Calvo assumption to express an infrequent price change.

2 Product Cycles and Prices

We start with a simple price model with negotiation for a price between two types of firms under a search and matching process in a goods market.

2.1 Negotiation between Firm A and Firm B

For price setting, two types of firms, firms A and firms B, negotiate the goods price in a search and matching market. Firms A are identical except in timing for matching with firms B, and firms A exist in an infinite number of a measure one and so do firms B. Firm B can be either a productive firm or a seeker firm for goods, where the number of seekers is given by u_t. A productive firm produces Z_t^B nominal units of goods B. To be productive, a firm must obtain Z^A real units of goods A from firms A.

A goods market for goods A is characterized by search frictions, and the flow cost of searching for a vacancy is $\kappa > 0$ paid by firms B. In period t, with probability s_t, a seeker firm B is matched with a firm A. Firm B then receives Z^A units of goods A, produces Z_t^B of goods B, gives it to the next agent in a chain of goods, and pay back $\widetilde{P}_t^A Z^A$ to firm A. We assume that Z_t^B is a nominal variable and includes a random price for simplicity.[3] Finally, at the end of period t, the product chain is dissolved with probability $\rho \in (0, 1)$, in which case firm A and B separate and then search for new matches for production and price setting in the next period $t + 1$. Note that there is one period lag for production after a new match. With probability $1 - \rho$, a contract survives and firm B again receives goods A in period $t + 1$. We call ρ the separation rate.

Here, the aggregate price P_t^A for goods A is determined by firm A and B through the sequence of Nash negotiation. Moreover, a new price $\widetilde{P}_t^A$ for goods A is set by only newly matched firms following the spirit of Shimer (2004) and Hall (2005) as shown in following sections.

We assume a free entry into a market of goods A. Thus, in equilibrium, the value of a seeker firm is zero, and hence the cost of searching must equal the expected revenue, or

$$\kappa = \beta s_t \mathrm{E}_t Q_{t+1}(\widetilde{P}_{t+1}^A), \tag{1}$$

Here, $Q_t(\widetilde{P}_t^A)$ is the value of a productive firm B as

$$Q_t(\widetilde{P}_t^A) = Z_t^B - Z^A \widetilde{P}_t^A + \beta(1 - \rho)\mathrm{E}_t Q_{t+1}(\widetilde{P}_t^A). \tag{2}$$

[3] We introduce a price for goods B in several ways in following sections.

The first two terms on the right-hand side (RHS) of equation (2) show the net current profit from production, while the third term is the discounted present value of future profit. We assume κ as a constant for simplicity.

From equations (2), we have

$$Q_t(\widetilde{P}_t^A) = Z_t^B - \frac{Z^A}{1-\beta(1-\rho)}\widetilde{P}_t^A + \frac{Z^A\beta(1-\rho)}{1-\beta(1-\rho)}\mathrm{E}_t\widetilde{P}_{t+1}^A + \beta(1-\rho)\mathrm{E}_tQ_{t+1}(\widetilde{P}_{t+1}^A). \quad (3)$$

Firm A produces goods A using an exogenous resource with a cost. This resource can include a labor input through a production function even though we do not specify it in this stage. To search for a seeker of firm B, firm A must post offers, which we call "vacancies". Posting vacancies is costless, but total goods production by firm A is capped at $Z^A N^*$ due to a limit of technology of N^*.

Therefore, the number of vacancies v_t is expressed as

$$v_t = N^* - (1-\rho)N_t, \quad (4)$$

where N_t is the number of firms A. In period t, a vacancy is filled with probability q_t. Thus, N_t evolves according to

$$N_{t+1} = (1-\rho)N_t + q_t v_t. \quad (5)$$

In such settings, the value of a new match for a firm A is

$$J_t^1(\widetilde{P}_t^A) = Z^A\widetilde{P}_t^A - X_t + \beta\mathrm{E}_t\left[(1-\rho)J_{t+1}^1(\widetilde{P}_t^A) + \rho J_{t+1}^0\right], \quad (6)$$

where X_t is an exogenous cost for production. The first term on the RHS shows current profit from sales, while the second term represents the discounted present value of a future profit.

On the other hand, the value of a vacancy for a firm A is

$$J_t^0 = \beta\mathrm{E}_t\left[q_tJ_{t+1}^1(\widetilde{P}_{t+1}^A) + (1-q_t)J_{t+1}^0\right]. \quad (7)$$

Since a vacancy yields no current profit, it has only discounted future values. These two equations imply that the surplus of a firm A from a new match is

$$J_t^1(\widetilde{P}_t^A) - J_t^0 = Z^A\widetilde{P}_t^A - X_t + \beta\mathrm{E}_t\left\{(1-\rho)\left[J_{t+1}^1(\widetilde{P}_t^A) - J_{t+1}^0\right] - q_t\left[J_{t+1}^1(\widetilde{P}_{t+1}^A) - J_{t+1}^0\right]\right\}, \quad (8)$$

and so

$$J_t^1(\widetilde{P}_t^A) - J_t^0 = \frac{Z^A}{1-\beta(1-\rho)}\widetilde{P}_t^A - \beta(1-\rho)\frac{Z^A}{1-\beta(1-\rho)}\mathrm{E}_t\widetilde{P}_{t+1}^A - X_t \\ + \beta\mathrm{E}_t\left[(1-\rho-q_t)(J_{t+1}^1(\widetilde{P}_{t+1}^A) - J_{t+1}^0)\right]. \tag{9}$$

Note that a price is determined by the future condition including a matching expectation. Thus, price decision is forward-looking.

2.2 Goods Market with Search Friction

The number of new matches in a period is given by a Cobb-Douglas matching function

$$m\left(u_t, v_t\right) = \chi u_t^{1-\alpha} v_t^{\alpha},\ \chi, \alpha \in (0,1). \tag{10}$$

Defining supply and demand for goods A in a market as

$$\theta_t = \frac{u_t}{v_t}, \tag{11}$$

we obtain

$$s_t = \chi\theta_t^{-\alpha}, \tag{12}$$

$$q_t = \chi\theta_t^{1-\alpha}, \tag{13}$$

$$N_t = (1-\rho)N_{t-1} + \chi\theta_{t-1}^{1-\alpha}v_{t-1}. \tag{14}$$

The price of goods A is determined according to Nash bargaining between the newly matched firm A and firm B. Thus, $\widetilde{P}_t^A$ solves

$$\max_{\widetilde{P}_t^A}\left[Q_t(\widetilde{P}_t^A)\right]^{1-b}\left[J_t^1(\widetilde{P}_t^A) - J_t^0\right]^b, \tag{15}$$

where $b \in (0,1)$ is the bargaining power for firm A. The first-order condition with respect to $\widetilde{P}_t^A$ yields

$$bQ_t(\widetilde{P}_t^A) = (1-b)\left[J_t^1(\widetilde{P}_t^A) - J_t^0\right]. \tag{16}$$

The aggregate price P_t^A of goods A is given by

$$N_tP_t^A = (1-\rho)N_{t-1}P_{t-1}^A + \chi\theta_{t-1}^{1-\alpha}v_{t-1}\widetilde{P}_t^A. \tag{17}$$

2.3 Linearized Price Equation

Linearized price equations are convenient to reveal the features of price dynamics. We log-linearize the price equations around a constant steady-state equilibrium. We express the log-deviation of a variable (e.g., P_t) from its efficient steady-state value ($\bar{P}$ or P) by placing a hat ($\widehat{\ }$) over the lower case symbol ($\widehat{p}_t$).

Linearized price dynamic equation is given by equations (1), (3), (9), (12), (13), (14), (16), and (17) as[4]

$$\pi_t^A = \beta\,(1-\rho)\,\mathrm{E}_t\pi_{t+1}^A + \gamma^\theta\widehat{\theta}_t + \gamma^x x_t + \epsilon_t, \tag{18}$$

$$\pi_t^A \equiv \widehat{p}_t^A - (1-\rho)\widehat{p}_{t-1}^A, \tag{19}$$

$$\gamma^\theta \equiv \rho\beta\bar{q}\,[1-\beta(1-\rho)]\,\frac{b\bar{Q}}{Z^A}, \tag{20}$$

$$\gamma^x \equiv \rho(1-b)\,[1-\beta(1-\rho)]\,\frac{\bar{X}}{Z^A}, \tag{21}$$

$$\epsilon_t \equiv \rho b\,[1-\beta(1-\rho)]\,\frac{Z^B}{Z^A}\widehat{Z}_t^B. \tag{22}$$

This is a price dynamic equation in a goods market with search and matching. We call this equation as a Search-based Phillips curve.

This curve shows several features for price dynamics. First, the present price is determined by a lagged price and expected price. Expected price is included in the equation due to an infrequent price change in a forward-looking behavior as shown in equations (8) and (9). A lagged price is included since an aggregate price is given by the weighted sum of a new price and the unchanged price of survival goods from a previous period as shown in equation (17). When this expected price and the lagged price increase, the present price increases.

Second, a goods market condition has an effect on prices. When market tightness increases, price increases. A response of price to a market condition is more sensitive as a product separation rate ρ becomes larger since an aggregate price depends more on newly set price. The probability of filling vacancy $\bar{q}$ appears for demand and supply. This probability is a matching probability in a goods market in a supply side. When

[4] For simplicity, we assume that a steady-state price is one.

matching probability increases, a price response to a demand and supply increases since a chance to set a new price depending on a demand and supply increases. Bargaining power also plays an important role. When an allocation of value $b\bar{Q}$ to firms A, i.e., supplier, increases, a price response to market tightness increases.

Third, a production cost is included in the curve from equation (6). When the cost of production increases, price increases. A effect of production cost on price depends on parameters for a goods market.

Forth, a shock in another market has an effect on price dynamics. As the separation rate and bargaining power of firms A increase, price response to a shock increases.

3 Introducing Product Cycles and Prices into a New Keynesian Model

Now we extend our model to a general equilibrium model. We basically introduce a Search-based Phillips curve into an economy of Trigari (2009) and Monacelli, Perotti, and Trigari (2010). They assume a search and matching in a labor market and flexible wage negotiation between a household and firms. We, however, introduce a search and matching in a goods market with infrequent price change. There are three types of agents, firms, a household, and a central bank. Household is a large family as given by Merz (1995). There are shopper-workers in a family. They match with firms and then provide labor forces through wage negotiation with firms and buy consumption goods through price negotiation with firms. Only when firms match with shopper-workers, firms produce consumption goods by a production function using labor force. Goods prices are sticky as in the last section. These goods are heterogeneous only due to the timing of production.

3.1 Household

An infinitely lived representative household derives utility u from real aggregated consumption C_t and disutility from labor supply $l_t(i)$, and discounts the future with discount factor $\beta \in (0,1)$. In period t, the household enjoys total real aggregate consumption and receives Π_t as a real lump-sum profit from firms, and T_t as a net real lump-sum transfer from the government. In addition, the household deposits D_t into a bank account, to be repaid at the end of period t with a nominal interest rate $R_t^D - 1$, where R_t^D is a policy variable of monetary policy.

For an aggregated consumption, we assume that the consumer's utility from consumption is increasing and concave in the consumption index of bundles of differentiated goods as in Benigno and Benigno (2003).

$$C_t \equiv \left[\left(\frac{1}{N_t} \right)^{\frac{1}{\varepsilon}} \int_0^{N_t} c_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{23}$$

where $\varepsilon \in (1,\infty)$ is the elasticity of substitution among intermediate goods. This consumption index has a property that prefers product variety out of symmetric equilibrium in which firms are homogeneous in any aspect.[5] Household chooses each $c_t(i)$ to minimize cost $\int_0^{N_t} p_t(i)c_t(i)di$, given the level of C_t and the price of each intermediate good, $p_t(i)$. This minimization yields

$$c_t(i) = \left[\frac{p_t(i)}{P_t} \right]^{-\varepsilon} \frac{C_t}{N_t}, \tag{24}$$

where the price index is given by

$$P_t \equiv \left[\frac{1}{N_t} \int_0^{N_t} p_t(i)^{1-\varepsilon} di \right]^{\frac{1}{1-\varepsilon}}. \tag{25}$$

In a demand function, when the number of a product increases, a demand for each good decreases due to preference of product variety through a cost minimization problem, i.e., the same amount of consumption across goods is better.[6]

For convenience in following sections, we define

$$c_{t,s}(i) = \left[\frac{p_t(i)}{P_s} \right]^{-\varepsilon} \frac{C_s}{N_s}. \tag{26}$$

[5]In symmetric equilibrium, this index just implies that the number of products multiplied by a production is an aggregate consumption as in Bilbiie, Ghironi, and Melitz (2012) that assume a consumption index by such as Dixit and Stiglits (1977). It is easy to introduce the same consumption index in Bilbiie, Ghironi, and Melitz (2012) into our model.

[6]Unlike Bilbiie, Ghironi, and Melitz (2012), a relative price does not change by the number of products in a price index of equation (25).

We have similar definitions for the firm's production and labor supply.

Then, the household's intertemporal problem is

$$\max_{\{C_{t+i},D_{t+i}\}_{i=0}^{\infty}} \mathrm{E}_t \sum_{i=0}^{\infty} \beta^i u(C_{t+i}, G_{t+i}), \tag{27}$$

subject to the budget constraint

$$P_t C_t + D_t = R_{t-1}^D D_{t-1} + W_t L_t + \Pi_t + T_t, \tag{28}$$

where P_t denotes the price of C_t, W_t denotes the wage of L_t, and

$$L_t = \int_0^{N_t} l_t(i) di. \tag{29}$$

The household's period utility function is

$$u(C_t, G_t) \equiv \frac{C_t^{1-\sigma}}{1-\sigma} - G_t, \tag{30}$$

where $\sigma > 0$ is the coefficient of relative risk aversion. The variable G_t denotes the familys disutility from supplying labor, i.e., the sum of the disutilities of worker-shopper who are employed as defined in Trigari (2009).

This optimization problem leads to

$$\lambda_t = C_t^{-\sigma}, \tag{31}$$

$$1 = \beta \mathrm{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{P_t}{P_{t+1}} R_t^D \right], \tag{32}$$

where λ_t is the Lagrange multiplier on the budget constraint (28).

Regarding consumption for individual goods and labor supply, there are worker-shoppers in a large family. Worker-shoppers go to a goods market and match with firms under a search friction. Then, they provide labor forces with wage negotiation with firms and buy consumption goods with price negotiation with firms. To decide a goods price and wages, each worker-shopper maximizes an additional utility contribution to a large family by a new match in a goods market Q_t.

$$Q_t \left(p_t \left(i\right), W_t\right) = \frac{W_t}{P_t} l_{t,t} \left(i\right) - \frac{g\left(l_{t,t}\left(i\right)\right)}{\lambda_t} + \left(1-\rho\right) \beta_{t,t+1} \mathrm{E}_t Q_{t+1} \left(p_t \left(i\right), W_{t+1}\right), \tag{33}$$

where λ_t is a marginal utility of consumption, $\beta_{t,t+1} \equiv \beta \frac{\lambda_{t+1}}{\lambda_t}$ is a stochastic discount factor, and $g\left(l_{t,t}\left(i\right)\right)$ is disutility from the labor supply of each member in a large family as follows.

$$g\left(l_{t,t}\left(i\right)\right) \equiv \frac{l_{t,t}^{1+\phi}\left(i\right)}{1+\phi}, \tag{34}$$

where ϕ^{-1} is Frisch elasticity of the labor supply to wages. This value is given by a family's marginal utility in an additional match in a goods market as shown in Trigari (2009) and Monacelli, Perotti, and Trigari (2010).[7] Note that wage is common for all workers and is set by newly matched worker-shoppers and firms. Thus, wage is flexible in a sense that wage is set every period.

For worker-shoppers, we assume free entry into a goods market. Thus, in equilibrium, the value of a seeker is zero, and hence the cost of searching must equal the expected revenue, or

$$\kappa = s_t Q_t(p_t(i), W_t), \tag{35}$$

where κ is a constant search cost. To simplify a model, a search cost does not consume consumption goods and is a tax to enter a market. This cost is finally returned to a household through transfer.[8]

3.2 Firms

Firms exist in an infinite number of a measure one. They can be productive when they match with worker-shoppers belonging to a large family in a goods market. Firm i employs worker $l_{t,t}(i)$ from a household to produce an consumption goods through a

[7]Note that an additional match in a goods market requires that an additional match in a labor market in our model. Under a heterogeneous goods price model, we additionally assume that price and wage are homogeneous to set the value function since worker-shoppers do not know which price and wage negotiation is assigned to them. Otherwise, we can assume that the economy is in symmetric equilibrium before negotiation for price and wage by each worker-shopper and firm.

[8]When a search cost consumes consumption goods, a resource constraint includes the number of matches as in Bilbiie, Ghironi, and Melitz (2012).

linear production function.

$$y_{t,t}(i) = A_t l_{t,t}(i), \tag{36}$$

where A_t is a technology shock. Note that there is no lag between a match and production. To search for a worker-shopper, a firm must post offers, which we call "vacancies". Posting vacancies is costless, but total number of matches is capped at N^*. The number of vacancies v_t is expressed as

$$v_t = N^* B_t - (1-\rho) N_{t-1}, \tag{37}$$

where N_t is the number of matches between firms and a household and B_t is a shock to the goods market. This shock changes the capacity of production. In period t, a vacancy is filled with probability q_t. Thus, N_t evolves according to

$$N_t = (1-\rho) N_{t-1} + q_t v_t. \tag{38}$$

In such settings, the value of a new match for an intermediate goods producer i is

$$J_t^1(p_t(i), W_t) = \frac{p_t(i)}{P_t} y_{t,t}(i) - \frac{W_t}{P_t} l_{t,t}(i) + \beta_{t,t+1} \mathrm{E}_t \left[(1-\rho) J_{t+1}^1(p_t(i), W_{t+1}) + \rho J_{t+1}^0 \right]. \tag{39}$$

The first two terms on the RHS shows a net current profit from sales while the second term represents the discounted present value of a future profit. Note that a firm negotiate a price only in timing of new matches with a worker-shopper. On the other hand, the value of a vacancy for a firm is

$$J_t^0 = \beta_{t,t+1} \mathrm{E}_t \left[q_{t+1} J_{t+1}^1(p_{t+1}(i)) + (1 - q_{t+1}) J_{t+1}^0 \right]. \tag{40}$$

Since a vacancy yields no current profit, it has only discounted future values. These two equations imply that the surplus of a firm from a new match is

$$\begin{aligned} J_t^1(p_t(i), W_t) - J_t^0 = {} & \frac{p_t(i)}{P_t} y_{t,t}(i) - \frac{W_t}{P_t} l_{t,t}(i) \\ & + \beta_{t,t+1} \mathrm{E}_t \left\{ (1-\rho) \left[J_{t+1}^1(p_t(i), W_{t+1}) - J_{t+1}^0 \right] - q_{t+1} \left[J_{t+1}^1(p_{t+1}(i), W_{t+1}) - J_{t+1}^0 \right] \right\}. \end{aligned} \tag{41}$$

Note that the surplus of a firm is expressed in a real term rather than a nominal term in Section 2.

3.3 Goods Market and Resource Constraint

The number of new matches in a period is given by a Cobb-Douglas matching function

$$m\left(u_t, v_t\right) = \chi u_t^{1-\alpha} v_t^{\alpha},\ \ \chi, \alpha \in (0,1)\,. \tag{42}$$

Defining supply and demand for consumption goods in a market as

$$\theta_t = \frac{u_t}{v_t}, \tag{43}$$

we obtain

$$s_t = \chi \theta_t^{-\alpha}, \tag{44}$$

$$q_t = \chi \theta_t^{1-\alpha}, \tag{45}$$

$$N_t = (1-\rho) N_{t-1} + \chi \theta_t^{1-\alpha} v_t. \tag{46}$$

A consumption goods price and wage for labor supply are determined according to Nash bargaining between the newly matched worker-shopper and firm. Given a demand function for consumption goods by equation (26), $\widetilde{p}_t$ and $\widetilde{W}_t$ solve

$$\max_{\widetilde{p}_t, \widetilde{W}_t} \left[Q_t(\widetilde{p}_t, \widetilde{W}_t)\right]^{1-b} \left[J_t^1(\widetilde{p}_t, \widetilde{W}_t) - J_t^0\right]^b, \tag{47}$$

where $\widetilde{p}_t$ is a relative price $\frac{p_t}{P_t}$ and $b \in (0,1)$ is the bargaining power for a firm. The first-order conditions with respect to $\widetilde{p}_t$ and $\widetilde{W}_t$ yields

$$-bQ_t(\widetilde{p}_t, \widetilde{W}_t) \frac{\partial}{\partial \widetilde{p}_t} \left[J_t^1(\widetilde{p}_t, \widetilde{W}_t) - J_t^0\right] = (1-b) \left[J_t^1(\widetilde{p}_t, \widetilde{W}_t) - J_t^0\right] \frac{\partial}{\partial \widetilde{p}_t} Q_t(\widetilde{p}_t, \widetilde{W}_t), \tag{48}$$

$$bQ_t(\widetilde{p}_t, \widetilde{W}_t) = (1-b) \left[J_t^1(\widetilde{p}_t, \widetilde{W}_t) - J_t^0\right]. \tag{49}$$

Note that a new price $\widetilde{p}_t$ and a new wage $\widetilde{W}_t$ are the same across newly matched worker-shoppers and firms.

The aggregate price P_t of consumption goods is given by

$$P_t^{1-\varepsilon} = \frac{q_t v_t}{N_t} \widetilde{p}_t^{1-\varepsilon} + \frac{(1-\rho)\, N_{t-1}}{N_t} P_{t-1}^{1-\varepsilon}. \tag{50}$$

Finally, a resource constraint is given by

$$C_t = A_t L_t. \tag{51}$$

3.4 Closed and Linearized Economy

We linearize a model around a constant steady state. From equations (31) and (32), we have a standard IS equation.

$$\widehat{C}_t = \mathrm{E}_t \widehat{C}_{t+1} - \sigma^{-1} \left(\widehat{R}_t - \mathrm{E}_t \pi_{t+1} \right), \tag{52}$$

where $\pi_t \equiv \widehat{p}_t - \widehat{p}_{t-1}$. The IS equation defines a relationship between demand and a real interest rate.

From equations (48), (49) and (54), we have a Search-based Phillips curve.

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \frac{1 - (1-\rho)\beta}{1 + \varepsilon \phi} \frac{\rho}{1-\rho} \left[(\sigma + \phi) \widehat{C}_t - \phi \widehat{N}_t - \phi \widehat{A}_t \right]. \tag{53}$$

This Search-based Phillips curve defines a relationship between demand, market conditions, and price.[9] The curve includes the number of matches in a goods market as a new explanatory variable for an inflation rate in addition to consumption. Moreover, the Search-based Phillips curve includes a separation rate in a goods market that determines a degree of price response to the number of matches and consumption, i.e., slope of the curve.

From equations (33), (37), (41), (45), (46) and (49), we have two equations for search friction in a goods market.

$$\widehat{N}_t = (1-\rho)(1-\bar{q}) \widehat{N}_{t-1} + \rho \widehat{q}_t + \frac{\bar{q} N^*}{\overline{N}} \widehat{B}_t, \tag{54}$$

$$\widehat{q}_t = \psi_1^q \mathrm{E}_t \widehat{q}_{t+1} + \psi_2^q \widehat{\beta}_{t,t+1} + \psi_3^q \widehat{C}_t + \psi_4^q \widehat{N}_t + \psi_5^q \widehat{A}_t, \tag{55}$$

where

$$\psi_1^q \equiv \frac{\beta}{\alpha} \left[\alpha (1-\rho) - b\bar{q} \right], \tag{56}$$

$$\psi_2^q \equiv \frac{\beta}{\alpha (1-\alpha)} (1 - b\bar{q} - \rho), \tag{57}$$

$$\psi_3^q \equiv \frac{1-b}{\alpha(1-\alpha)\overline{Q}} \frac{\overline{y}}{\varepsilon} \left[1 - \frac{\varepsilon - 1}{1 + \phi} \sigma \right], \tag{58}$$

[9] Surpluses in a real term by equations (33) and (41) change a coefficient of an expected inflation rate and introduce a simple inflation rate in a Search-based Phillips curve.

$$\psi_4^q \equiv -\frac{1-b}{\alpha\left(1-\alpha\right)\overline{Q}}\frac{\overline{y}}{\varepsilon}, \tag{59}$$

$$\psi_5^q \equiv \frac{1-b}{\alpha\left(1-\alpha\right)\overline{Q}}\frac{\varepsilon-1}{\varepsilon}\overline{y}. \tag{60}$$

Equation (54) shows the transition of the number of matches in a goods market. Equation (55) shows that the probability of a match for firm $\widehat{q}_t$ depends on economic conditions such as the discount factor, consumption, and the number of matches in a goods market. These equations express an endogenous interaction between goods market friction and price dynamics. This interaction is closely related to parameters for a goods market, such as a separation rate b, a probability of a match in a steady state $\bar{q}$, an elasticity of matches α, and a bargaining power parameter b.

Coefficients of ψ_1^q, ψ_2^q, and ψ_3^q take negative and positive values according to parameters. For reasonable calibrations, a coefficient for the number of matches in the future ψ_1^q is positive as shown in following sections. A coefficient for a stochastic discount factor ψ_2^q is positive for reasonable calibrations. When a stochastic discount factor increases, a probability of a match for a firm (household) increases (decreases) from a free entry condition in equations (35) since values of firm and household in equations (33) and (41) increase. A coefficient for consumption ψ_3^q can be negative and positives within a reasonable range of parameters, mainly those such as the elasticity of substitution among intermediate goods ε, Frisch elasticity of labor supply to wages ϕ^{-1}, and the coefficient of relative risk aversion $\sigma > 0$. These parameters sufficiently change according to former studies. For larger values of these parameters, a coefficient for consumption tends to be negative. A coefficient for the number of matches ψ_4^q is negative. When the number of matches increases, values for firms and a household decrease since a demand for differentiated goods and a relative price decrease due to preference of product variety given an aggregate demand. Then, from a free entry condition, a probability of match for a firm (household) decreases (increases).

To close an economy, we assume a following Taylor type rule.

$$\widehat{R}_t = (1-\psi^R)\psi^\pi \pi_t + (1-\psi^R)\psi^C \widehat{C}_t + \psi^R \widehat{R}_{t-1}, \tag{61}$$

where ψ^R, ψ^π, and ψ^C are positive parameters.

4 Inspecting a Model

4.1 Baseline Calibration

Regarding product turnover rate ρ, Broda and Weinstein (2010) show that product turnover rate at the product level in the United States is about 25 percent annually. Ueda, Watanabe, and Watanabe (2016) show that a product turnover rate generally fluctuate in a range between 30 and 40 percent annually for Japan using the point of sale scanner data including retail goods. Price adjustment occurs in the timing of product turnover and more than half of products do not experience price changes until their exit from the market. Thus, as baseline case we set ρ to be equal to 0.08 (an average between 25 and 40 percents). For a parameter in a goods market, following Bilbiie, Ghironi, and Melitz (2012) we set elasticity of substitution across goods ε as 3.8. We set the elasticity of matches in a goods market α to be equal to 0.5. We set the bargaining power parameter b to be equal to 0.5. For a parameter regarding labor supply, we set the Frisch elasticity of labor supply to wages ϕ^{-1} as 0.1 following Trigari (2009). For a demand side and monetary policy, we set the coefficient of relative risk aversion as 2 as in Eggertsson and Woodford (2003). Following Steinsson (2008), we set $\psi^{\pi} = 2$, $\psi^{C} = 0.5$, and $\psi^{R} = 0.85$ for a monetary policy rule. A quarterly discount factor β is given by 0.99 as a conventional value. A steady state value of technology $\bar{A}$ and a maximum number of matches N^* are given by 1. We set the number of matches in a steady state $\bar{N}$ to be 0.83 since an average idleness rate is 17.3 percent in the manufacturing sector in the U.S. as shown in Michaillat and Saez (2015). Then we can calculate $\bar{q} = 0.28$ from a steady state relationship.[10] Note that a steady state value $\bar{q}$ works as a parameter as shown in equation (55).

Following Bilbiie, Ghironi, and Melitz (2012), we set the persistence of productivity shock A_t as 0.979. We also assume a goods market shock B_t with a persistence of 0.979. Ueda, Watanabe, and Watanabe (2016) indicate that the number of products increases by two hundred percent during the last twenty years. Thus, a number of product can

[10]From steady state relationships, we calculate $\bar{C} = 0.83$, $\bar{l} = \bar{y} = 1.0$, $\bar{W} = 0.25$, and $\bar{Q} = 2.1$.

increase very persistently. We assume such a situation in simulation.

4.2 Role of Goods Market Friction on Price Dynamics

A new feature for a model is given by a matching mechanism in a goods market. A Search-based Phillips curve includes the number of matches in a goods market. This term comes from a demand function for equation (24). When the number of matches increases, a demand for differentiated goods decreases due to a preference for product variety and the inflation rate (for an average price) decreases.

It is useful for interpretation to merge two equations for a goods market. From equations (54) and (55), we have[11]

$$\widehat{N}_t = \psi_1^N \mathrm{E}_t \widehat{N}_{t+1} + \psi_2^N \widehat{N}_{t-1} + \psi_3^N \widehat{C}_t + \psi_4^N \mathrm{E}_t \widehat{\beta}_{t,t+1} + \psi_5^N \widehat{A}_t + \psi_6^N \widehat{B}_t, \tag{62}$$

$$\psi_0^N \equiv \alpha + \beta (1-\rho)(1-\bar{q})\left[\alpha(1-\rho) - b\bar{q}\right] + \rho(1-\alpha)\frac{1-b}{\bar{Q}}\frac{\bar{y}}{\varepsilon}, \tag{63}$$

$$\psi_1^N \equiv (\psi_0^N)^{-1}\beta\left[\alpha(1-\rho) - b\bar{q}\right], \tag{64}$$

$$\psi_2^N \equiv (\psi_0^N)^{-1}\alpha(1-\rho)(1-\bar{q}), \tag{65}$$

$$\psi_3^N \equiv (\psi_0^N)^{-1}\frac{\rho(1-\alpha)(1-b)}{\bar{Q}}\frac{\bar{y}}{\varepsilon}\left[1 - \frac{\varepsilon-1}{1+\phi}\sigma\right], \tag{66}$$

$$\psi_4^N \equiv (\psi_0^N)^{-1}\beta\rho(1-\alpha)(1-b\bar{q}-\rho), \tag{67}$$

$$\psi_5^N \equiv (\psi_0^N)^{-1}\frac{\rho(1-\alpha)(1-b)}{\bar{Q}}\frac{\varepsilon-1}{\varepsilon}\bar{y}, \tag{68}$$

$$\psi_6^N \equiv \frac{\bar{Q}}{1-b}\frac{\alpha}{\alpha-1}\frac{q^*}{\rho\bar{N}}. \tag{69}$$

[11] Coefficients take negative and positive signs according to parameters. For reasonable calibrations, coefficients for the number of matches ψ_1^N and ψ_2^N are positives. Thus, the number of matches in a goods market makes persistent dynamics in a economy. A coefficient for consumption ψ_3^N can be negative and positives according to a reasonable range of parameters, mainly those such as the elasticity of substitution among intermediate goods ε, Frisch elasticity of labor supply to wages ϕ^{-1}, and the coefficient of relative risk aversion $\sigma > 0$. A coefficient for a stochastic discount factor ψ_4^N is positive for reasonable calibrations. When a stochastic discount factor increases, the number of matches increases since a value for production increases and probability of a match for a given vacancy increases.

Thus, matching friction in a goods market causes inflation persistence through a lag for the number of matches. This outcome is consistent with Bilbiie, Ghironi, and Melitz (2007) though a mechanism behind it is different between two papers. In Bilbiie, Ghironi, and Melitz (2007), there is no matching friction in a goods market. In our model, however, a matching friction, such as a match probability, contributes to inflation persistence. Note that all coefficients in an equation (62) are positive for a baseline calibration.

To look at the effects of parameters in a goods market, we first change the separation rate, i.e., ρ, from a baseline calibration. Nakamura and Steinsson (2012) show that 70 percent of goods are replaced with two or less price changes after introduction into a goods market. We assume a more frequent separation and set $\rho = 0.16$ for as extension. This is a situation where a firm once separates and matches with a new shopper and worker when re-setting price for the same goods. Figure 1 shows responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent productivity shock. For a positive productivity shock, the inflation rate decreases. For a larger separation rate, a price is more flexible, i.e., a steeper slope in the curve, and a negative price response is larger. The number of matches increase in response to the shock since a coefficient for a productivity shock in equation (62) is positive. A larger separation rate gives a smaller increase in the number of matches since coefficients for the future and past number of matches are smaller in equation (62).[12] Figure 2 shows the responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent goods market shock. An increase of the number of products causes a long term deflation under an economic expansion. For a larger separation rate, price response is larger. Note that a separation rate appears in a Search-based Phillips curve and an equation for the number of matches. Thus, these outcomes are given by combined effect from two equations. An effect from a Search-based Phillips curve, however,

[12]When we change the separation rate, the coefficient for a productivity shock changes. It, however, does not change the outcome here. For other simulations in this section, results qualitatively do not change even when we assume the same size shock for different parameters.

is dominant for an inflation rate, consumption, and interest rate since these variables show larger responses for a larger separation rate. When an effect from an equation for the number of matches is dominant, all responses are smaller for a larger separation rate.

When we restrict the role of a market, a Search-based Phillips curve is independent from the number of matches in a market and is similar to a standard New Keynesian model. For example, we assume a constant match in a market, i.e., $v_t q_t = \overline{N}^*$ and an entry cost is time-varying. Then variation of the number of matches is zero, i.e., $\hat{N}_t = 0$ and an entry cost changes to keep a constant number of matches. Then, a Search-based Phillips curve induces a New Keynesian Phillips curve with the Calvo's price adjustment mechanism as a special case.

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \frac{1 - (1-\rho)\beta}{1 + \varepsilon\phi} \frac{\rho}{1-\rho} \left[(\sigma + \phi) \widehat{C}_t - \phi \widehat{A}_t \right]. \tag{70}$$

A matching mechanism, however, in a goods market directly determines price dynamics. The slope of the curve becomes steeper as a product separation rate ρ becomes larger. This is sharply in contrast to other papers that introduce price stickiness into general equilibrium models. For example, in a New Keynesian Phillips curve with Calvo (1983) - Yun (1996) price adjustment, so called Calvo parameter that determines the probability of price change decides a slope of the curve. In Bilbiie, Ghironi, and Melitz (2007), a parameter of a price adjustment cost sets the slope of the Phillips curve.

We then change the probability of match in a goods market in a steady state, i.e., $\bar{q}$, and assume $\bar{q}$ to be double at 0.56.[13] Figure 3 shows responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent productivity shock. For the larger probability of a match in a steady state, the probability of a match gives a weaker response to a shock as shown in equation (62) in which a coefficient for the expected probability of a match becomes smaller. This is because a negative response of vacancy to the number of matches in the last period become stronger as the probability

[13]To set $\bar{q} = 0.56$, we calibrate $\bar{N} = 0.94$.

of a match in a steady state increases.[14] This reduces the fluctuation in the number of matches as shown in equation (54). Eventually, the number of matches increase less since coefficients for the future and past number of matches in equation (62) are smaller. Then, an inflation rate decreases less in response to the shock. Note that the probability of a match gives an effect only on an equation for the number of matches (62). Thus, these outcomes are purely given by the equation. Figure 4 shows responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent goods market shock. For a larger probability of a match, all variables show smaller responses.

We change the elasticity of matches to a vacancy posting in a matching function, i.e., α, to 0.8. Figure 5 shows responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent productivity shock. When the elasticity of matches increases, the probability of a match gives a stronger response to a shock as shown in equation (55) in which a coefficient for the expected probability of a match becomes larger. Thus, when we assume the same size shock for a different elasticity of matches, responses become larger for a larger elasticity of matches. However, when we change the elasticity of matches, coefficients for shocks also change in equation (62). For a larger elasticity of matches, these coefficients become smaller. For two factors, all responses become smaller for a larger elasticity of matches. For a goods market shock, however, we have a different outcome. All responses become larger for a larger elasticity of matches as shown in Figure 6 that shows responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent goods market shock. Note that the probability of a match gives an effect only on an equation for the number of matches. Thus, these outcomes are purely given by the equation.

We also change the bargaining power for a firm, i.e., b, to 0.8. Figure 7 shows

[14] Linearization of equation (54) is intuitive on this point.

$$\widehat{v}_t = \frac{N^*}{\bar{N}}\frac{\bar{q}}{\rho}\widehat{B}_t - (1-\rho)\frac{\bar{q}}{\rho}\widehat{N}_{t-1}. \tag{71}$$

This is because a steady state value of vacancy becomes smaller and the same amount of increase/decrease of vacancy in a level needs a larger change in log-deviation from a steady state as $\bar{q}$ becomes larger.

responses of the inflation rate, consumption, the number of matches, and the interest rate to a 1 percent productivity shock. When the bargaining power for firms increases, the probability of a match gives a weaker response to a shock as shown in equation (55) in which a coefficient for the expected probability of a match becomes smaller. This is because firms are reluctant to respond to an economic situation under strong bargaining power. This effect is dominant in simulations even though coefficients for shocks also change for different bargaining powers. For a bargaining power, all responses become smaller. Figure 8 shows a similar result for a 1 percent goods market shock.

These simulations show that features in a goods market significantly change economic dynamics, such as price and consumption.

5 Future Extension

There is a great possibility to extend a Search-based Phillips curve. For future extension, we evaluate the performance of Search-based Phillips curve in a rich general equilibrium model. It would be also of interest to show optimal criteria for a model with a Search-based Phillips curve. A product chain through a search and matching in a goods market is also an interesting topic for future research.

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Table 1: Parameter Values

Parameters	Values	Explanation
β	0.99	Discount Factor
ρ	0.08	Product Entry Rate
b	0.5	Bargaining Power for Firms
α	0.5	Elasticity of Match of Supplier
ϕ^{-1}	0.1	Frisch Elasticity of Labor Supply to Wages
ε	3.8	Elasticity of Substitution across Goods
σ	2	Coefficient of Relative Risk Aversion
ψ^R	0.85	Coefficient for Lagged Interest Rate in Taylor Rule
ψ^π	2	Coefficient for Inflation Rate in Taylor Rule
ψ^C	0.5	Coefficient for Consumption in Taylor Rule
$\bar{N}$	0.83	Number of Match in a Steady State
$\bar{q}$	0.28	Probability of Match in a Steady State

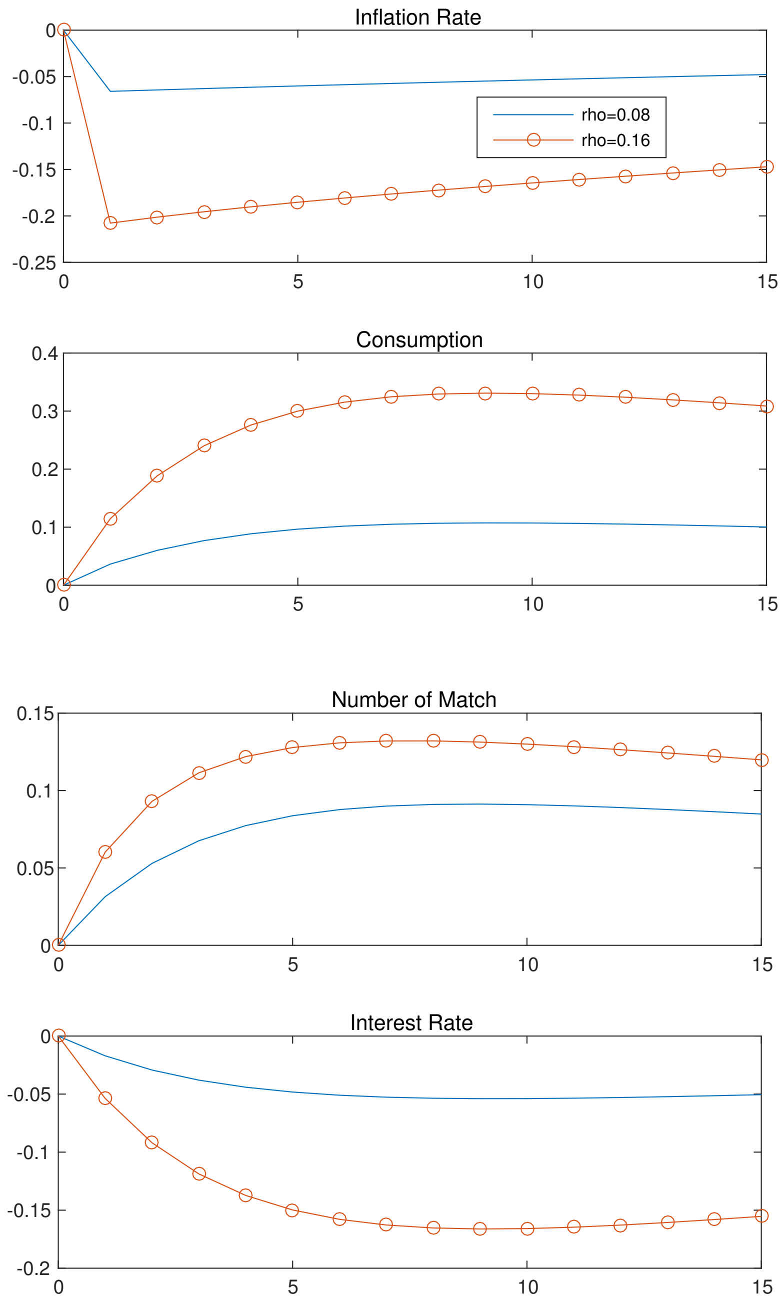

Figure 1: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Productivity Shock for Different Separation Rates.

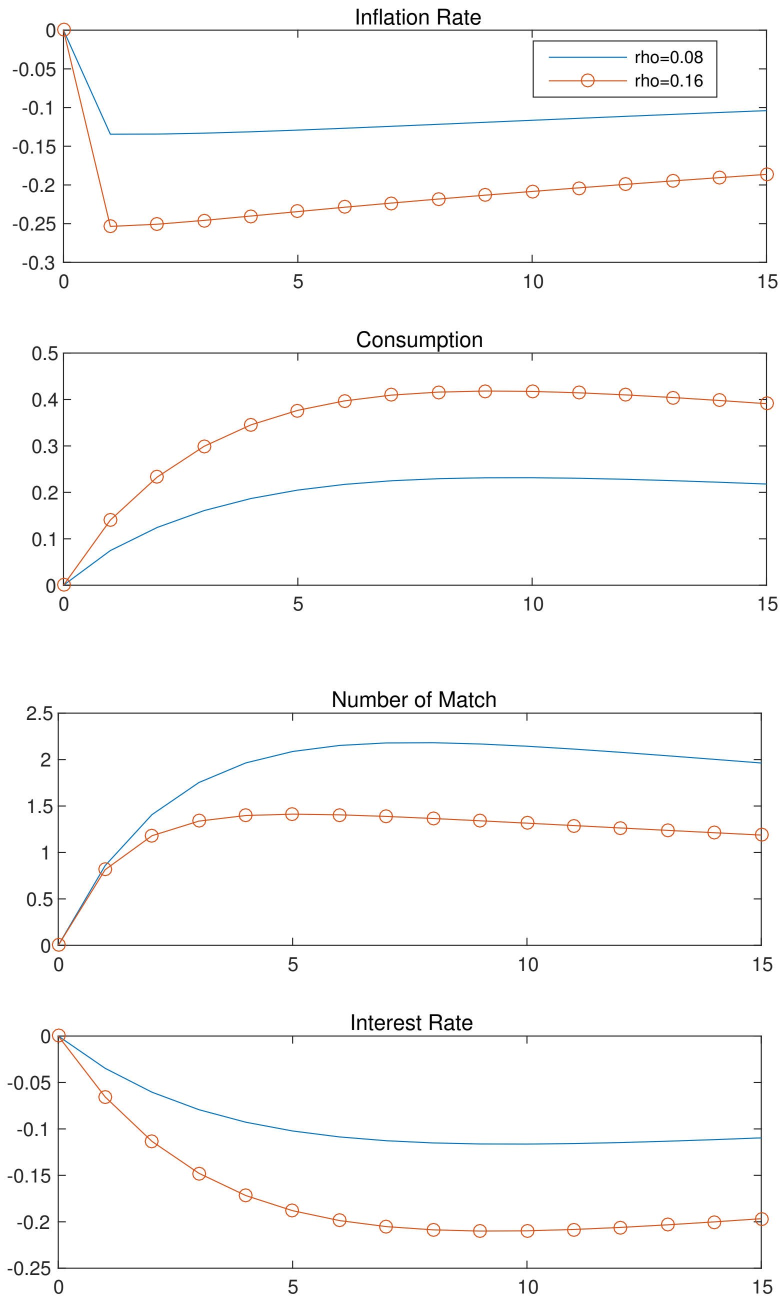

Figure 2: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Goods Market Shock for Different Separation Rates.

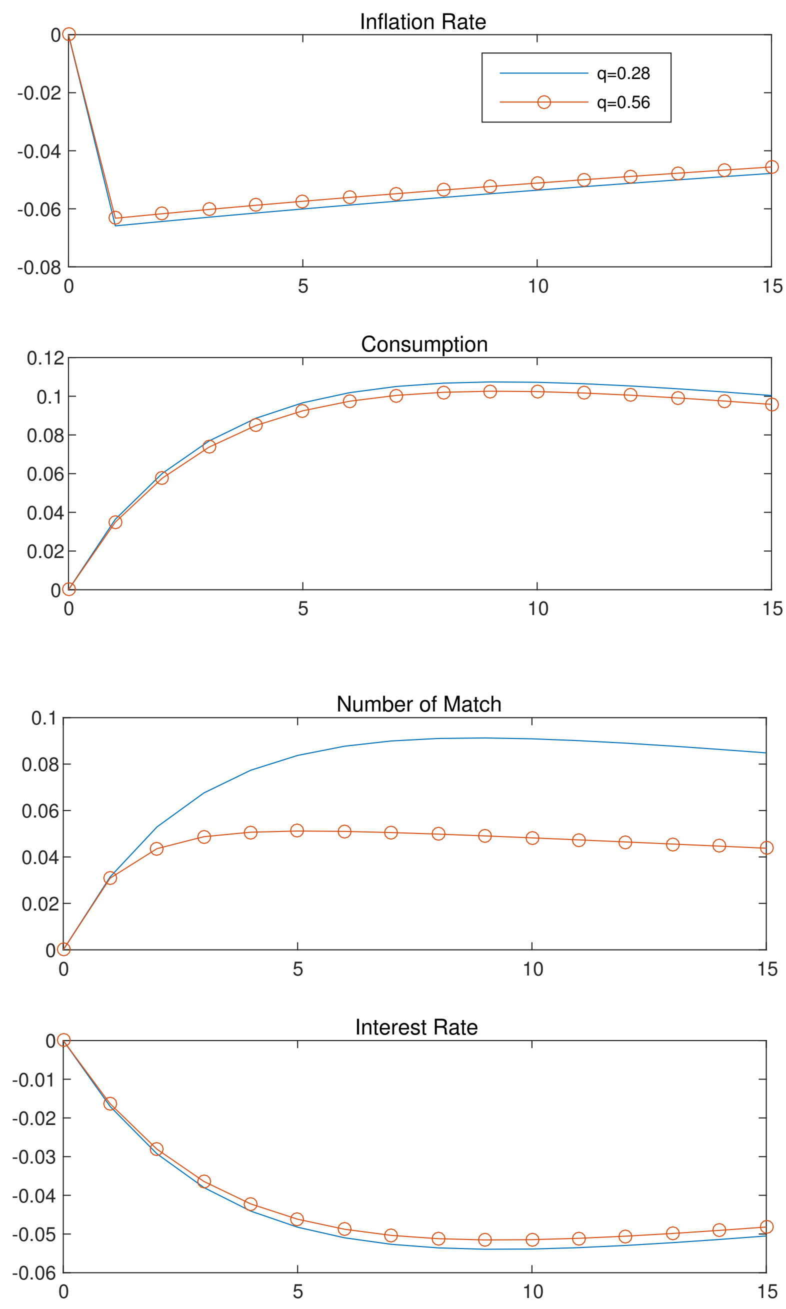

Figure 3: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Productivity Shock for Different Probability of Match.

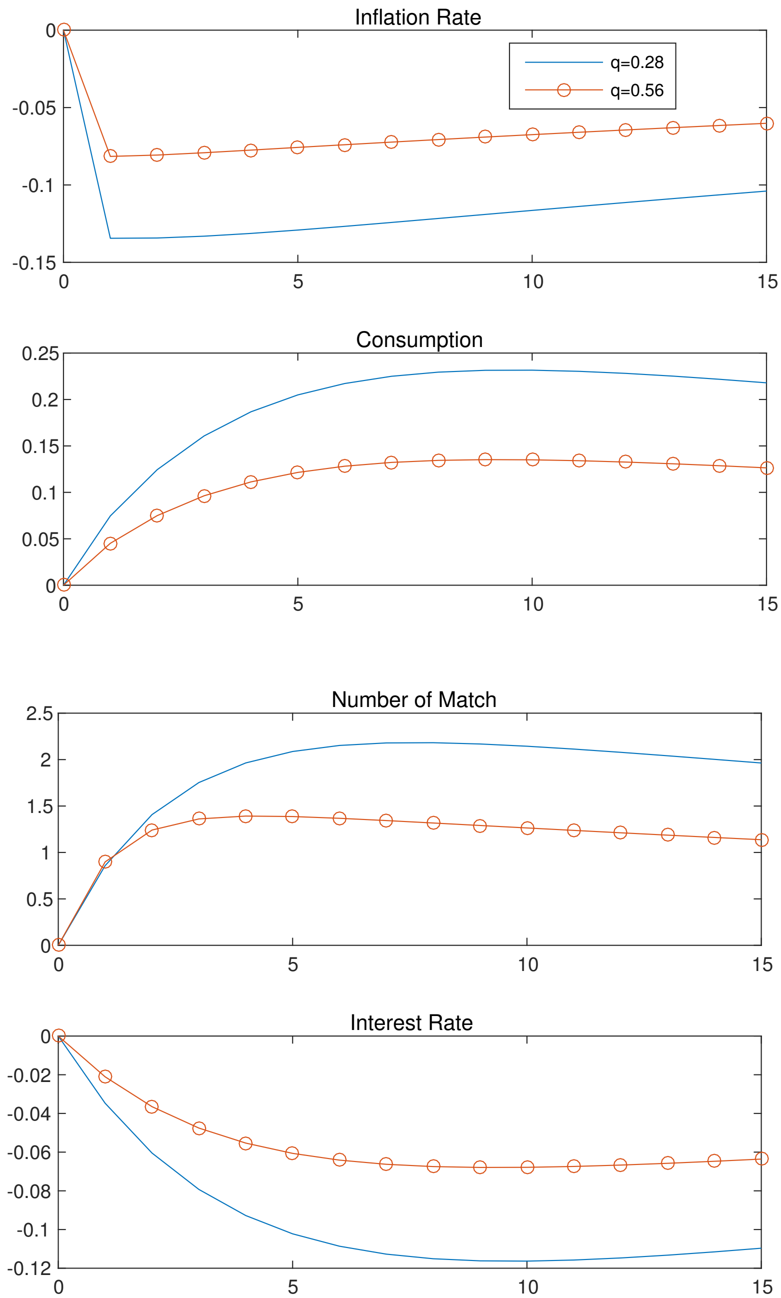

Figure 4: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Goods Market Shock for Different Probability of Match.

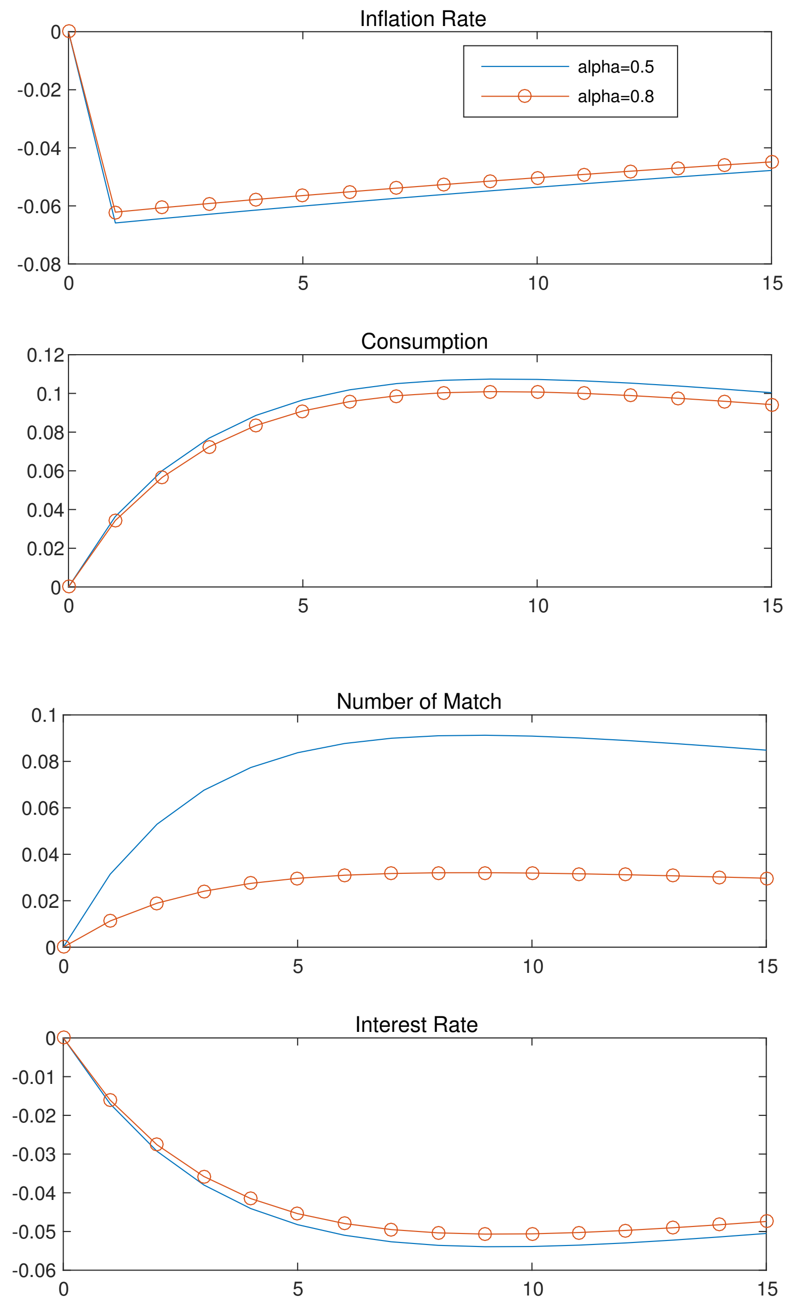

Figure 5: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Productivity Shock for Different Matching Elasticity.

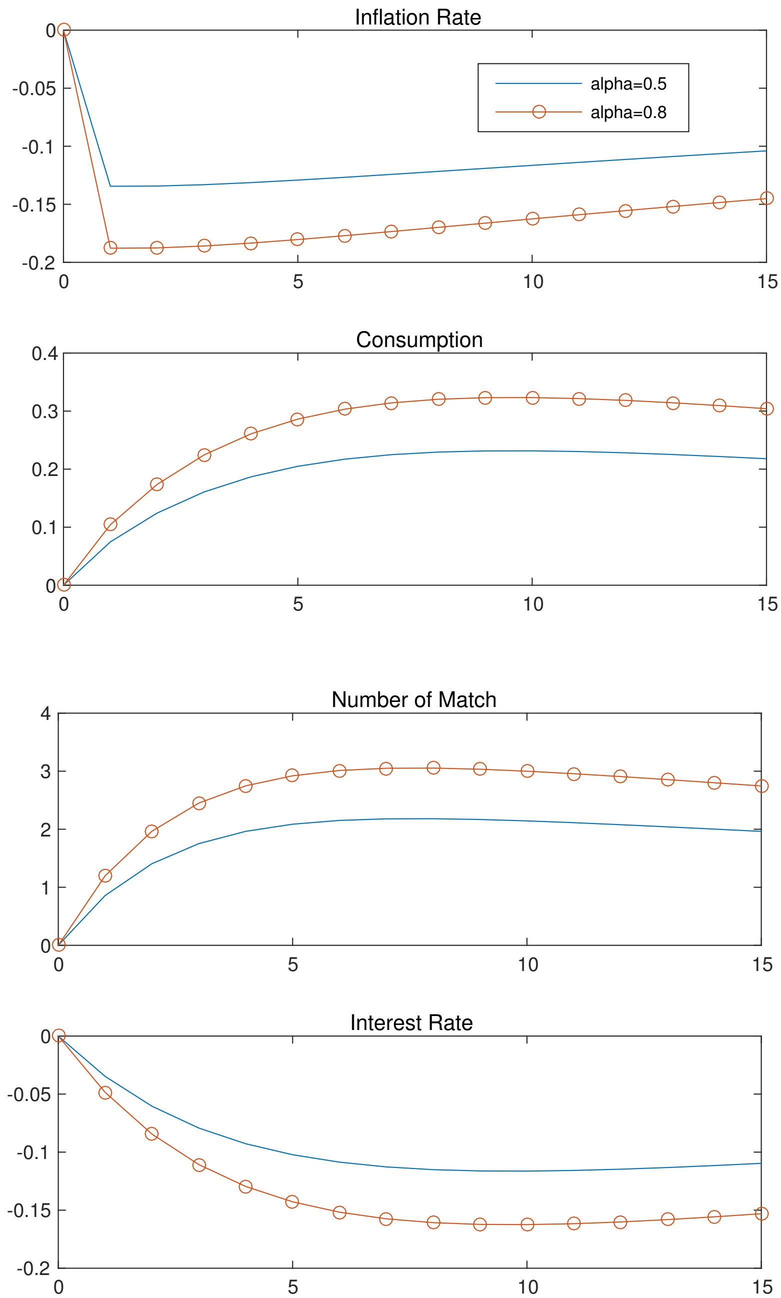

Figure 6: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Goods Market Shock for Different Matching Elasticity.

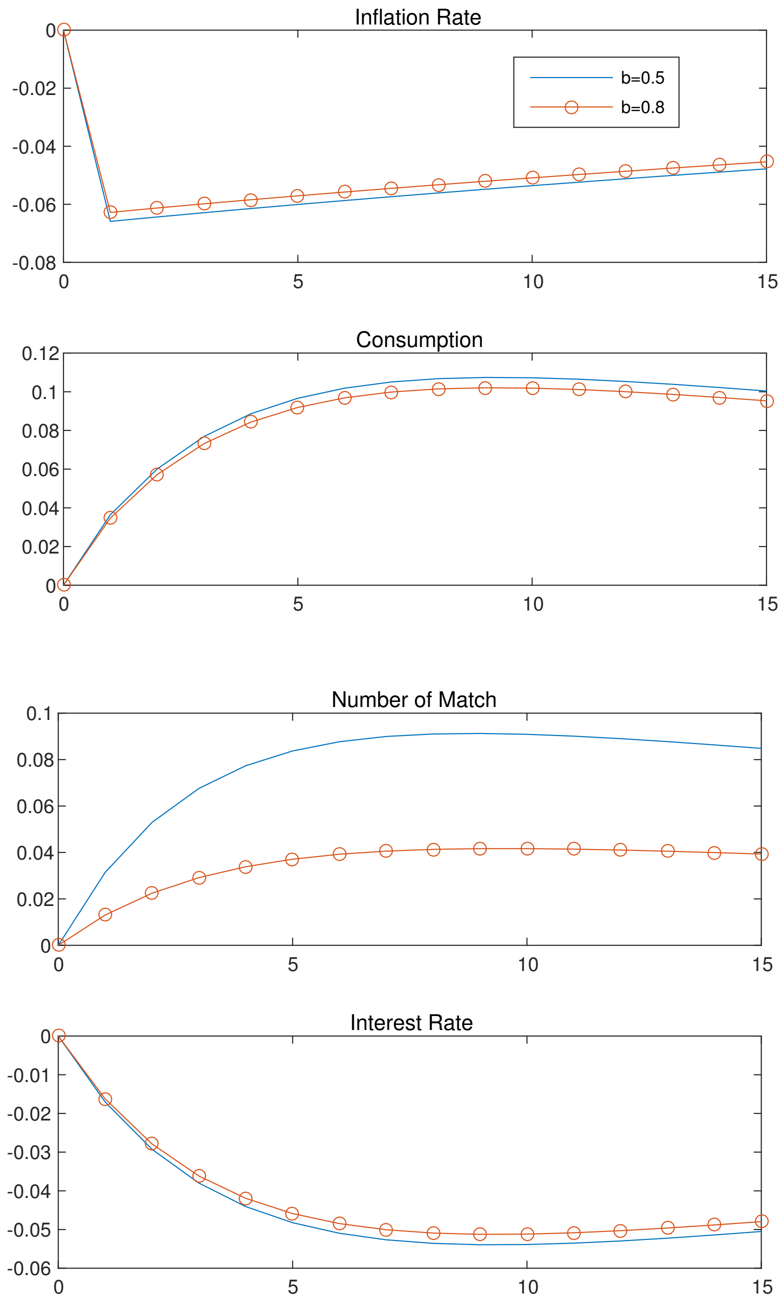

Figure 7: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Productivity Shock for Different Bargaining Power.

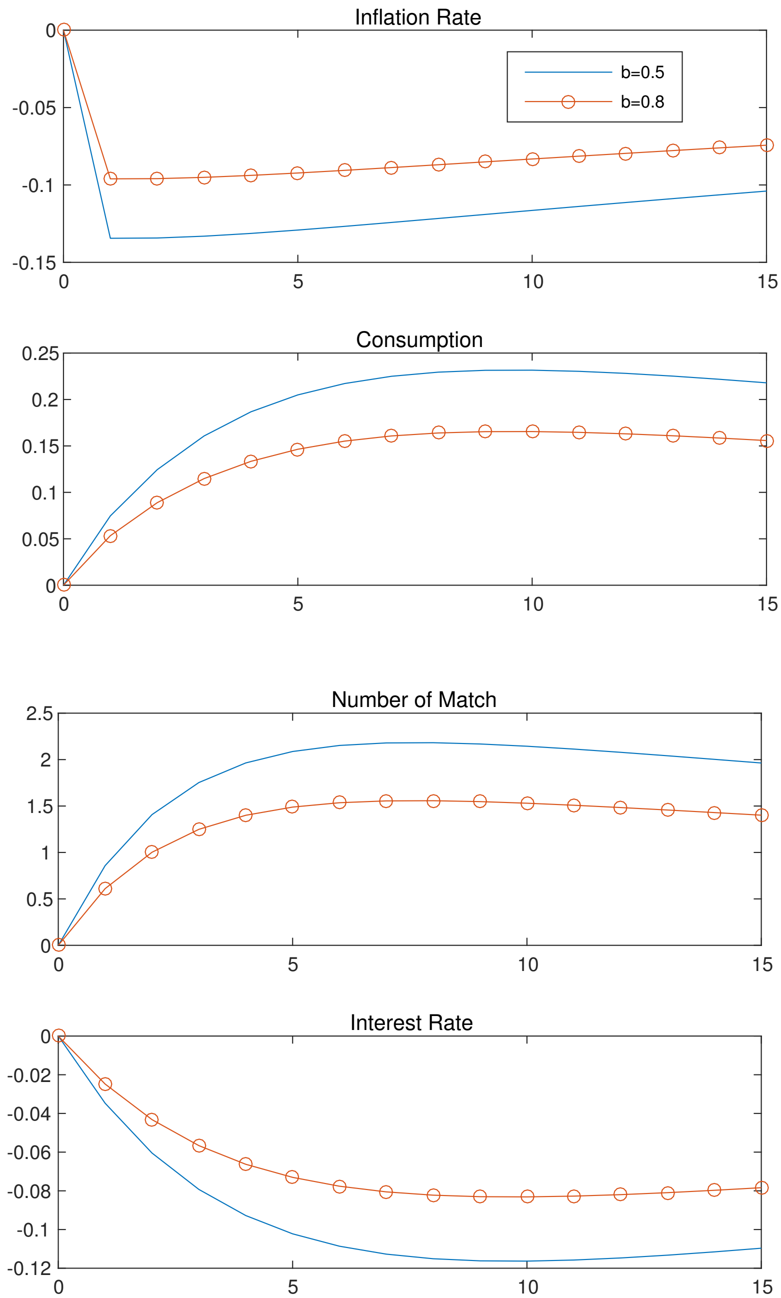

Figure 8: Response of Inflation Rate, Consumption, Number of Match, and Interest Rate to Goods Market Shock for Different Bargaining Power.