Non-Separability and Sectoral Comovement in a Sticky Price Model*

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Abstract

Strong procyclical fluctuations in durable production are the most prominent feature of the empirical response to monetary shocks. This paper investigates the role of preferences in matching this feature of the data in a two-sector sticky price model with flexibly priced durables. The reaction of durables depends crucially on whether preferences are separable between labor and aggregate consumption. When preferences are separable, the model exhibits perverse behavior. Flexibly priced durables contract during periods of economic expansion. However, a sticky price model with non-separable preferences can replicate the empirically plausible response of durable spending. The key to the model's success hinges upon the fact that the non-separable preferences imply the complementarity between aggregate consumption and labor supply, absent in the separable preferences. Finally, we present empirical evidence supporting the non-separable preferences.

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1 Introduction

Durable goods feature prominently in discussions of monetary policy. According to the data, the durable goods sector is one of the sectors that seem to respond most procyclically to monetary policy.[1] However, as demonstrated by Barsky, House, and Kimball (2003, 2007), it is difficult to match this feature of the data by simply incorporating durable goods into sticky price models with separable preferences. In particular, if durable goods have flexible prices, but nondurable goods prices are sticky, then an expansionary monetary policy leads to an *increase* in nondurable goods production but a *decline* in durable goods production, so that aggregate output may not change at all. The comovement problem arises.

This paper seeks to resolve this sectoral comovement puzzle in a two-sector sticky price model with flexibly priced durable goods. First, we analytically demonstrate that the two-sector sticky price model, if modified to feature the non-separability between aggregate consumption and labor in household's preferences, can generate the response of durable spending to a monetary policy shock documented in empirical studies. The key mechanism to generate this result is the complementarity between nondurable consumption and labor implied by the non-separable preferences, absent in the separable preferences. We also show that variable capital utilization with imperfect capital mobility helps expand the threshold level of the non-separability required for the model to generate the sectoral comovement in response to a monetary shock.

Second, we show that the non-separable preferences are indeed supported by the data and the estimated degree of non-separability is strong enough to resolve the comovement problem. To this end, we estimate the intertemporal elasticity of substitution that controls the degree of non-separability using a Bayesian approach. Our estimates of the intertemporal elasticity of substitution are well below unity suggesting that the data favor non-separable preferences. Furthermore, the Bayesian model comparison picks the model with the non-separable preferences over the one with the separable preferences, unless one has an extremely strong prior belief about the separable preferences.

Our empirical results complement the previous studies by Basu and Kimball (2002) and Guerron-Quintana (2008), who also report evidence against the separable preferences. However, our empirical specification differs from theirs in two ways. While their empirical specifications abstract from durable spending in estimating the intertemporal elasticity of substitution, we explicitly incorporate durable spending in the estimation. The earlier studies use the limited information approach. Basu and Kimball (2002) employs a method of moments on the Euler equation and Guerron-Quintana (2008) uses a minimum distance estimator. Instead, we employ the full information approach that explores the full range of empirical implications conveyed by the model.

Why is the complementarity between nondurable consumption and labor, implied by non-

[1] Erceg and Levin (2006) document that an exogenous increase in the interest rate, estimated through a structural VAR, reduces consumer durables and residential investment spending nearly three times more than nondurable consumption. Barsky, House, and Kimball (2003) also report similar results using the Romer dates as indicators of exogenous changes in monetary policy. Following the Romer date, the production of durables falls far more than that of nondurables.

separable preferences, a key for the model generating the comovement in response to a monetary shock?[2] This stems from the fact that the complementarity significantly affects the reaction of a nominal wage to a monetary expansion. Following such an expansion, the nominal wage tends to rise because nondurable-goods producing firms raise the demand for labor inputs to meet their increased demands due to sticky prices. For producers in the flexibly priced durable sector, the increase in factor price is merely an adverse cost shock. Unless there are forces offsetting the rise in the cost of production, the flexible-price sector contracts. However, the complementarity between nondurable consumption and labor supply mitigates the rising pressure on the nominal wage since the increase in nondurable consumption shifts the labor supply curve out. Hence, if the degree of complementarity is large enough, production in the durable sectors could rise.[3] Variable capital utilization in turn strengthens the effects of the complementarity on offsetting a rise in the nominal wage, so that it expands the range of the non-separability consistent with the sectoral comovement.

In addition to incorporating non-separable preferences, there are several ways to resolve the comovement problem. Barsky, House, and Kimball (2003, 2007) suggest the introduction of a sticky nominal wage as one possible solution to the comovement problem. Carlstrom and Fuerst (2006) explicitly demonstrate that a sticky wage helps generate sectoral comovement. Another way suggested by Barsky, House, and Kimball (2003, 2007) is to consider the model with a credit constraint. Monacelli (2009) confirms this with numerical simulations. Finally, Bouakez, Cardia, and Ruge-Murcia (2011) show that incorporating input-output interactions and limited factor mobility leads to positive comovement across sectors.

The remainder of the paper is organized as follows. Section 2 describes a two-sector sticky price model that includes nondurable and durable goods. Section 3 presents an analytical treatment that provides insight into why the non-separable preferences can solve the comovement problem. Section 4 estimates our model and shows that the estimated degree of non-separability is strong enough to produce a procyclical response of durable spending to a monetary shock. Section 5 concludes.

2 The Model

In this section, we extend the two-sector sticky price model of Barsky, House, and Kimball (2003, 2007) by incorporating non-separability between aggregate consumption and labor, and by introducing variable capital utilization.

The economy is populated by a constant number of identical, infinitely-lived households, continua of firms in two sectors that respectively produce differentiated durable and nondurable goods, perfectly competitive final goods firms in two sectors, and a monetary authority.

[2]The non-separability between aggregate consumption and labor also implies that the service flow from durable goods and labor are complementary. However, the complementarity between the consumption of durable services and labor has little impact on the behavior of the model. It is because the stock of durable goods changes so slightly following the monetary shock as Barsky, House, and Kimball (2003, 2007) show.

[3]Barsky, House, and Kimball (2003, 2007) briefly discuss the possibility that the complementarity between nondurables and labor might temper the negative comovement problem, but have never explored it formally.

2.1 Households

The representative household receives utility from consumption of the nondurable goods, enjoys the service flow from durable goods, and incurs disutility from hours worked. Let C_t and S_t respectively denote period t consumption of the nondurable goods and the service flow from the durable consumption, and let L_t denote labor supply. The household maximizes the expected lifetime utility, given by

$$U_0 = E_0 \left[\sum_{t=0}^{\infty} \beta^t U(C_t, S_t, L_t) \right], \tag{1}$$

where $\beta \in (0, 1)$ is the subjective discount factor.

We modify the conventional King-Plosser-Rebelo monetary utility function used by Basu and Kimball (2002) and Shimer (2009) to include the consumption of the service flow from durable goods. The specific form of $U(\cdot)$ adopted in this paper is

$$U(C_t, S_t, L_t) = \frac{Z_t^{1-\frac{1}{\sigma}} \left(1 + \left(\frac{1}{\sigma} - 1\right) v(L_t)\right)^{\frac{1}{\sigma}} - 1}{1 - \frac{1}{\sigma}}, \tag{2}$$

where $Z_t = \left(\psi_c C_t^{1-\frac{1}{\rho}} + \psi_d S_t^{1-\frac{1}{\rho}} \right)^{\frac{\rho}{\rho-1}}$ and $v(L_t) = \phi \frac{\eta}{1+\eta} L_t^{\frac{\eta+1}{\eta}}$. Z_t is a quantity index that aggregates the consumption of nondurable goods and durable services, and $v(L_t)$ measures the disutility incurred from hours worked with $v^{'} > 0$, $v'' > 0$. Our formulation departs from Barsky, House, and Kimball (2003, 2007) in that we relax the assumption of additive separability between aggregate consumption and labor. In (2), the degree of non-separability is controlled by a parameter for the intertemporal elasticity of substitution, σ. The lower this parameter is, the larger the non-separability displayed by the utility function. The separable case, for instance, corresponds to $\sigma \to 1$:

$$\lim_{\sigma \to 1} U(C_t, S_t, L_t) = \log(Z_t) - v(L_t).$$

This separable preference is used in most sticky price models, including Barsky, House, and Kimball (2003, 2007).

The stock of durable goods evolves according to

$$D_t = X_t + (1 - \delta) D_{t-1}, \tag{3}$$

where $\delta \in (0, 1)$ is the depreciation rate and X_t denotes newly purchased durables. Following the literature, the service flow from durable goods, S_t, is assumed to be proportional to the stock of the durable goods, D_t and, without loss of generality, the coefficient of proportionality is normalized to 1:

$$S_t = D_t = X_t + (1 - \delta) X_{t-1} + (1 - \delta)^2 X_{t-2} + \cdots .$$

The household enters period t with a stock of private one-period nominal bonds (B_{t-1}), and a fixed stock of capital ($\overline{K}$). During the period, the household receives wages, rentals on capital services, dividends paid by firms, and interest payments on bond holdings. These resources net of the cost of varying capital utilization rate are used to purchase durable and nondurable goods and to acquire assets to be carried over to the next period. Then, the household's budget constraint (in nominal term) is

$$P_{c,t}C_t + P_{x,t}X_t + B_t \leq W_t L_t + \sum_{j=c,x} R_{j,t}u_{j,t}\overline{K}_{j,t} + \Pi_t + (1+i_{t-1})B_{t-1} - \sum_{j=c,x} P_{j,t}a(u_{j,t})\overline{K}_{j,t}, \quad (4)$$

where the subscripts c and x denote variables that are specific to the nondurable and durable sector, respectively. $P_{c,t}$ and $P_{x,t}$ are the nominal prices of the nondurable and durable, W_t is the nominal wage rate,[4] Π_t are profits returned to the consumer through dividends, and i_t is the nominal interest rate. In addition, $\overline{K}_{j,t}$ is the productive capital stock in sector $j = c, x$ and $u_{j,t}$ denotes the capital utilization rate in sector $j = c, x$. Hence, $K_{j,t} \equiv u_{j,t}\overline{K}_{j,t}$ represents the capital services used in each sector and $R_{j,t}$ is the rental rate of capital services.[5] The increasing and convex function $a(u_{j,t})\overline{K}_{j,t}$ denotes the cost, in units of the goods in each sector, of setting the capital utilization rate to $u_{j,t}$. Following Christiano, Eichenbaum, and Evans (2005), we impose two restrictions on the capital utilization function, $a(u_{j,t})$. First, we require that $u_{j,t} = 1$ in a steady state. Second, we assume $a(1) = 0$. Under these assumptions, the steady state of the model is independent of the curvature of the function $a(\cdot)$ in steady state, $\chi \equiv \frac{a''(1)}{a'(1)}$. The parameter χ governs the elasticity of capital utilization. A high value of χ corresponds to a small elasticity, implying that varying utilization is highly costly.

The first order conditions associated with the optimal choice of C_t, L_t and X_t are

$$\frac{\gamma_{c,t}}{P_{c,t}} = \frac{\gamma_{x,t}}{P_{x,t}}, \quad (5)$$

$$-U_L(C_t, D_t, L_t) = \gamma_{x,t}\frac{W_t}{P_{x,t}} = \gamma_{c,t}\frac{W_t}{P_{c,t}}, \quad (6)$$

where $\gamma_{c,t} \equiv U_C(C_t, D_t, L_t)$ denotes the marginal utility of nondurable consumption and $\gamma_{x,t}$ denotes the shadow value of durable consumption. As in Barsky, House, and Kimball (2007), $\gamma_{x,t}$ can be written as the present value of future marginal service flow from an additional unit of the durable at time t, discounted by the subjective rate of time preference and the depreciation rate:

$$\gamma_{x,t} = MU_t^D + \beta(1-\delta)E_t MU_{t+1}^D + \beta^2(1-\delta)^2 E_t MU_{t+2}^D + \cdots, \quad (7)$$

where $MU_t^D \equiv U_D(C_t, D_t, L_t)$ denotes the marginal utility of the service flows from an additional unit of the durable at time t.

[4]Note that we assume that labor can flow freely between sectors. Hence, wage rates are identical between sectors.

[5]Rental rates in different sectors might not be the same because we consider the case where capital stock is imperfectly mobile between sectors.

2.2 Firms

We assume the existence of a continuum of monopolistically competitive firms, indexed by $s \in [0, 1]$, producing differentiated intermediate goods in each sector. A final good in each sector is produced by a perfectly competitive, representative firm. The firm produces the final good by combining a continuum of intermediate goods.

2.2.1 Final goods firms

The final good in each sector is aggregated by the constant elasticity of substitution (CES) technology:

$$C_t = \left[\int_0^1 c_t(s)^{\frac{\varepsilon_c - 1}{\varepsilon_c}} ds \right]^{\frac{\varepsilon_c}{\varepsilon_c - 1}} \quad \text{and} \quad X_t = \left[\int_0^1 x_t(s)^{\frac{\varepsilon_x - 1}{\varepsilon_x}} ds \right]^{\frac{\varepsilon_x}{\varepsilon_x - 1}}, \tag{8}$$

where $c_t(s)$ and $x_t(s)$ are the quantity of intermediate goods s used as an input in each sector. Solving a cost minimization problem for the final good producer in each sector delivers the conditional demand for the intermediate goods

$$c_t(s) = \left(\frac{p_{c,t}(s)}{P_{c,t}} \right)^{-\varepsilon_c} C_t \quad \text{and} \quad x_t(s) = \left(\frac{p_{x,t}(s)}{P_{x,t}} \right)^{-\varepsilon_x} X_t, \tag{9}$$

where $p_{j,t}(s)$ is the price of intermediate good s in sector $j = c, x$ and $P_{j,t}$ is the aggregate price level in sector $j = c, x$. Finally, the zero-profit condition implies that

$$P_{j,t} = \left[\int_0^1 p_{j,t}(s)^{1-\varepsilon_j} ds \right]^{\frac{1}{1-\varepsilon_j}}, \quad \text{for} \quad j = c, x. \tag{10}$$

2.2.2 Intermediate goods firms

Intermediate good producers in each sector are monopolistically competitive. Each intermediate goods firm produces its differentiated goods using the following production function:

$$c_t(s) = A_t A_{c,t} F(k_{c,t}(s), l_{c,t}(s)) = A_t A_{c,t} k_{c,t}^{\alpha}(s) l_{c,t}^{1-\alpha}(s), \tag{11}$$

$$x_t(s) = A_t A_{c,t} F(k_{x,t}(s), l_{x,t}(s)) = A_t A_{c,t} k_{x,t}^{\alpha}(s) l_{x,t}^{1-\alpha}(s), \tag{12}$$

where A_t is an aggregate total factor productivity (TFP) shock and $A_{j,t}$ is a sectoral TFP shock in sector $j = c, x$, $l_{j,t}(s)$ and $k_{j,t}(s)$ are labor and capital in firms s in sector $j = c, x$ at time t. We assume that these aggregate and sectoral technology shocks follow the AR(1) processes:

$$\log(A_t) = \rho_A \log(A_{t-1}) + \xi_t, \tag{13}$$

$$\log(A_{j,t}) = \rho_{A_j} \log(A_{j,t-1}) + \xi_{j,t} \quad \text{for} \quad j = c, x. \tag{14}$$

Intermediate goods firms are assumed to set nominal prices in a staggered fashion, according to the stochastic time dependent rule proposed by Calvo (1983). Each firm in sector $j = c, x$ resets its price with the probability of $1-\theta_j$ each period, independently of the time elapsed since the last adjustment. Thus, for each period a measure $1-\theta_j$ of firms reset their prices, while a fraction θ_j firms keep their prices from the previous period. An intermediate goods firm resetting its price in period t in sector $j=c,x$ will seek to maximize the present value of expected future real profits generated while that price remains effective,

$$E_0\left[\sum_{t=0}^{\infty}\beta^t\theta_j^t\gamma_{j,t}\frac{\Pi_{j,t}}{P_{j,t}}\right], \tag{15}$$

subject to the sequence of demand constraints (9). Here $\gamma_{j,t}$ is the shadow value of the good produced in sector j and $\Pi_{j,t}/P_{j,t}$ measures the real value of an intermediate goods firm's profit in sector j in period t. It is easy to show that the optimal reset prices in sector $j=c,x$, denoted as $p^*_{j,t}$, are

$$p^*_{c,t}=\frac{\varepsilon_c}{\varepsilon_c-1}\frac{E_t\sum_{k=0}^{\infty}\beta^k\theta_c^k\left(\frac{\zeta_{c,t+k}}{P_{c,t+k}}\right)(P_{c,t+k})^{\varepsilon_{c,t}}\gamma_{c,t+k}C_{t+k}}{E_t\sum_{k=0}^{\infty}\beta^k\theta_c^k(P_{c,t+k})^{\varepsilon_{c,t}-1}\gamma_{c,t+k}C_{t+k}}, \tag{16}$$

and

$$p^*_{x,t}=\frac{\varepsilon_x}{\varepsilon_x-1}\frac{E_t\sum_{k=0}^{\infty}\beta^k\theta_d^k\left(\frac{\zeta_{x,t+k}}{P_{x,t+k}}\right)(P_{x,t+k})^{\varepsilon_{x,t}}\gamma_{x,t+k}X_{t+k}}{E_t\sum_{k=0}^{\infty}\beta^k\theta_d^k(P_{x,t+k})^{\varepsilon_{x,t}-1}\gamma_{x,t+k}X_{t+k}}, \tag{17}$$

where $\zeta_{j,t}$ is the nominal marginal cost in sector j. Finally, the equation describing the dynamics for the aggregate price level in sector $j=c,x$, is given by $P_{j,t}=\left[(1-\theta_j)(p^*_{j,t})^{1-\varepsilon_j}+\theta_j P_{j,t-1}^{1-\varepsilon_j}\right]^{1/(1-\varepsilon_j)}$.

2.3 Monetary Authority and Market Clearing

The monetary authority conducts monetary policy using the short-term nominal interest rate as the policy instrument. The gross nominal interest rate $R^n_t\equiv 1+i_t$ follows a Taylor rule of the following type:

$$R^n_t=(R^n)^{(1-\rho_R)}(R^n_{t-1})^{\rho_R}(\pi_t)^{\rho_\pi(1-\rho_R)}(Y^z_t)^{\rho_Y(1-\rho_R)}\exp(\xi_{R,t}), \tag{18}$$

where $\xi_{R,t}$ is a monetary policy shock, π_t is an economy-wide inflation rate, Y^z_t is the deviation of real GDP from its steady state. While a monetary policy shock is an unanticipated change in money supply in Barsky, House, and Kimball (2003, 2007), we replace it with a Taylor rule. It is widely accepted that the Taylor rule best describes the U.S. monetary policy over 1984-2007 period. To estimate the model, therefore, it seems more appropriate to model the monetary policy shock as an exogenous change in the policy interest rate rather than in the money supply. However, the key results of the paper go through if the monetary policy shock is introduced as an unanticipated change in the money supply.

We define real GDP Y_t as $Y_t \equiv P_c C_t + P_x X_t$, where P_c and P_x are steady state prices for the nondurable and durable good. The GDP deflator is then nominal GDP divided by real GDP and used for calculating an economy-wide inflation.

Finally, in equilibrium net private debt $B_t = 0$ and the labor and capital markets equilibriums require

$$L_t = L_{c,t} + L_{x,t} \quad \text{and} \quad \overline{K} = \overline{K}_{c,t} + \overline{K}_{x,t}, \tag{19}$$

where $L_{j,t} = \int l_{j,t}(s)ds$ and $\overline{K}_{j,t} = \int \overline{k}_{j,t}(s)ds$ is labor and the stock of capital used in sector $j = c, x$.

3 Analytical Discussion

In this section, we analytically show that the response of sticky price models to monetary policy shocks depends crucially on how we assume separability between aggregate consumption and labor in preferences. In particular, we find that the larger the non-separability displayed by the utility function, the more likely the model is to generate sectoral comovement. We then show that variable capital utilization with imperfect capital mobility expands the threshold level of non-separability needed to generate sectoral comovement. Since we focus on the reaction of the model to a monetary policy shock, we assume that there are no technology shocks in this analytical discussion. We will allow these shocks to operate in the estimation.

3.1 Why does non-separability affect the behavior of the model?

To understand the underlying mechanisms, through which non-separability affects the behavior of model, it is useful to rewrite the labor supply condition (6) in the following manner:

$$-U_L(C_t, D, \underbrace{L_{x,t} + L_{c,t}}_{L_t}) = \gamma_x \frac{W_t}{P_{x,t}} = \frac{\gamma_x}{\mu \zeta_{x,t}} W_t, \tag{20}$$

where the last equality is implied by the fact that the flexible price of durables is a constant markup (μ) over its marginal cost: $P_{x,t} = \mu \zeta_{x,t}$. Note that we drop the time script of D_t and $\gamma_{x,t}$ in the equation. Barsky, House, and Kimball (2003, 2007) show that the stock-flow ratio is high so that even large changes in purchases following a monetary shock have only minor effects on the total quantity of the durable good. Small deviations from the steady state of the economy virtually do not alter the stock of durables, and thus their shadow value ($\gamma_{x,t}$) is nearly constant at cyclical frequencies.

The nominal marginal cost $\zeta_{x,t}$ is the cost of hiring an additional unit of a productive input multiplied by the number of inputs required to produce an additional unit of durable goods. For now, let us assume that both physical capital and labor is perfectly mobile across sectors but the capital utilization rate in each sector remains constant. This corresponds to the case considered by Barsky, House, and Kimball (2007). Because the production functions in both sectors have constant returns to scale, and because physical capital and labor can flow freely across sectors, all firms have the same marginal cost and choose the same capital-to-labor ratios. Thus,

$$\zeta_{x,t} = \frac{W_t}{F_2(\overline{K}_{x,t}, L_{x,t})} = \frac{W_t}{F_2(\overline{K}, L_t)} = \frac{W_t}{f(L_t)}, \tag{21}$$

where $f(L_t) = F_2(\overline{K}, L_t) = (K/L_t)^{\alpha}$. Combining (20) and (21) yields

$$-U_L(C_t, D, \underbrace{L_{x,t} + L_{c,t}}_{L_t}) = \frac{\gamma_x}{\mu} f(\underbrace{L_{x,t} + L_{c,t}}_{L_t}). \tag{22}$$

This equation shows that the nature of the comovement problem is closely related to the separability between nondurable consumption and labor. First, suppose that the preference is separable ($\sigma = 1$). In this case, the marginal disutility from labor is only a function of labor, so that (22) becomes

$$v^{'}(\underbrace{L_{x,t} + L_{c,t}}_{L_t}) = \frac{\gamma_x}{\mu} f(\underbrace{L_{x,t} + L_{c,t}}_{L_t}). \tag{23}$$

This equation says that if the production of nondurables rises, then employment in the durable sector must fall in a model with separable preferences. The intuition behind this result is straightforward. Following a monetary expansion, nondurable goods firms with sticky prices increase production to meet demand instead of raising their prices. The incipient increase in output in the nondurable goods sector increases the demand for labor, which in turn raises marginal costs (i.e., an increase in disutility of work $v^{'}(\cdot)$ and a decrease in marginal product of labor $f(\cdot)$). For producers in the flexibly priced durable goods sector, the increase in marginal costs is merely an adverse supply shock. Because there are no forces that can offset a rise in the cost of production, this definitely lowers the labor employed in the durable goods sector and thus the production of durable goods falls.

However, things will be different in a model with non-separable preferences. When $\sigma < 1$, the cross-partial derivative, $-U_{LC}$ is negative in our monetary utility function, (2), which means that the increased level of nondurable consumption would reduce the marginal disutility of work. According to (22), the fact that the cross-partial derivative $-U_{LC} < 0$ implies that increased nondurable consumption shifts the labor supply curve out. This mitigates the rise in the nominal wage and marginal cost of producing durables and therefore it moderates the contraction in durable production. Since the complementarity between the consumption of nondurables and labor is decreasing with the parameter σ (i.e.,$\partial \left| -U_{LC} \right| / \partial \sigma < 0$), the extent to which production in the durable sector contracts gets smaller as σ takes lower values than unity.

3.2 What determines the range of the σ consistent with sectoral comovement?

It is instructive to log-linearize the equation (22) around a deterministic steady state to understand what factors determine the range of the parameter σ in which the model generates sectoral comovement. Define $\eta_{LL} \equiv \left(\frac{-U_{LL}L}{-U_L}\right)\Big|_{ss} > 0$ as the own elasticity of marginal disutility from labor and $\eta_{LC} \equiv \left(\frac{-U_{LC}C}{-U_L}\right)\Big|_{ss}$ as the cross-elasticity of marginal disutility from labor with respect to nondurable consumption, evaluated at the steady state. These elasticities are expressed as

$$\eta_{LL} = \frac{(1-\sigma)^2}{\sigma}\frac{WL}{P_C C}\frac{\psi_c C^{1-1/\rho}}{\psi_c C^{1-1/\rho} + \psi_d D^{1-1/\rho}} + \frac{1}{\eta} \tag{24}$$

and

$$\eta_{LC} = \left(1 - \frac{1}{\sigma}\right)\frac{\psi_c C^{1-1/\rho}}{\psi_c C^{1-1/\rho} + \psi_d D^{1-1/\rho}}, \tag{25}$$

respectively. Log-linearizing (22) around a non-stochastic steady state yields

$$\eta_{LC}\widehat{C}_t + \eta_{LL}(\omega_c \widehat{L}_{c,t} + \omega_x \widehat{L}_{x,t}) = -\alpha(\omega_c \widehat{L}_{c,t} + \omega_x \widehat{L}_{x,t}), \tag{26}$$

where a circumflex ("hat") over a variable represents proportionate deviations of that variable from its steady state and $\omega_j = L_j/L$ in sector $j = c, x$. Using the fact that all firms choose the same capital-to-labor ratio, we can write $C_t = \overline{K}_{c,t}^{\alpha} L_{c,t}^{1-\alpha} = \left(\frac{\overline{K}}{L_t}\right)^{\alpha} L_{c,t}$ and log-linearize it as follows:

$$\widehat{C}_t = \kappa_c \widehat{L}_{c,t} - \omega_x \widehat{L}_{x,t}. \tag{27}$$

Here $\kappa_c \equiv \frac{\partial \widehat{C}_t}{\partial \widehat{L}_{c,t}}$ is the elasticity of nondurable production with respect to labor in the nondurable and is equal to $(1 - \alpha\omega_c)$ when both physical capital and labor is perfectly mobile across sectors but capital utilization rate remains constant. Combining equation (27) with equation (26) yields

$$(-\eta_{LC}\alpha + \eta_{LL} + \alpha)\,\omega_x \widehat{L}_{x,t} = (-\eta_{LC}\kappa_c - (\eta_{LL} + \alpha)\omega_c)\,\widehat{L}_{c,t}. \tag{28}$$

This equation confirms a previous discussion that unless labor supply and the consumption of nondurables are complementary (i.e., $\eta_{LC} < 0$), it is impossible to obtain sectoral comovement. Given that $\eta_{LC} < 0$, the condition that generates the sectoral comovement is

$$-\eta_{LC}\kappa_c > \nu, \tag{29}$$

where $\nu = (\eta_{LL} + \alpha)\omega_c$. This condition has an intuitive interpretation. As discussed, when $L_{c,t}$ rises to meet higher demand in the nondurable goods following a monetary expansion, it has two offsetting effects on the costs of durable good production. The first term, $-\eta_{LC}\kappa_c$, quantifies the extent to which an increase in $L_{c,t}$ lowers costs of durable good production through the complementarity between labor supply and nondurable consumption. Higher values for κ_c strengthen the effects of the complementarity on lowering costs of durable good production. The second term, ν, measures the extent to which an increase in $L_{c,t}$ raises costs of durable good production by inducing a higher disutility of work ($\eta_{LL}\omega_c$) and a lower marginal product of labor ($\alpha\omega_c$). When the former dominates the latter, a positive response of durable goods production is obtained.

More importantly, the condition above clearly identifies what factors determine the range of the complementarity consistent with sectoral comovement. Higher values of κ_c and lower values of ν enable the model to generate sectoral comovement with a smaller degree of the complementarity, $-\eta_{LC}$. Below, we show that variable capital utilization with imperfect capital mobility increases the value of κ_c and lowers the value of ν.

To understand why imperfect capital mobility and variable capital utilization lead to a wider range of σ that generates sectoral comovement, it is useful to inspect something analogous to (22) in this case, which is given by

$$-U_L(C_t, D, L_{x,t} + L_{c,t}) = \frac{\gamma_x}{\mu}\left(\frac{u_{x,t}\overline{K}_x}{L_{x,t}}\right)^{\alpha}. \tag{30}$$

With imperfect capital mobility, labor in the nondurable sector has no impact on the marginal product of labor in the durable sector. Increased labor demand in the nondurable sector raises the cost of production in the durable sector only through a higher disutility of work. Hence, ν, which measures the extent to which an increase in $L_{c,t}$ raises the costs of durable production, decreases from $(\eta_{LL} + \alpha)\omega_c$ to $\eta_{LL}\omega_c$. Thus, a smaller complementarity is required to offset the rise in costs of production.

In addition, variable rate of capital utilization also helps expand the range of the parameter σ that is consistent with sectoral comovement since it increases the value for $\kappa_c \equiv \frac{\partial \widehat{C}_t}{\partial \widehat{L}_{c,t}}$. Variable capital utilization makes the supply of capital services strongly responsive to changes in the labor so that it is sometimes described as leading to short-run production that is nearly linear in labor.[6] As Shapiro (1993) shows, for example, increases in labor are accompanied by increases in the workweek of capital, one measure of capital utilization. Loosely speaking, this observation allows us to write production function as

$$C_t = (u_{c,t}\overline{K}_c)^{\alpha} L_{c,t}^{1-\alpha} = \left(\frac{u_{c,t}\overline{K}_c}{L_{c,t}}\right)^{\alpha} L_{c,t} \simeq BL_{c,t},$$

where $B = \left(\frac{u_c\overline{K}_c}{L_c}\right)^{\alpha}$. Thus, variable capital utilization might increase κ_c, the elasticity of non-durable goods production with respect to $L_{c,t}$, from $(1 - \alpha\omega_c)$ to 1.

Obviously, the extent to which variable capital utilization increases κ_c depends on how costly varying capital utilization is, which is controlled by the parameter χ. When varying utilization becomes more costly (i.e., higher χ), an increase in κ_c tends to be smaller, so that a stronger complementarity is required for the model to obtain sectoral comovement.

[6] Previous papers that have used this type production function include Bils and Cho (1994) and Ramey and Shapiro (1998).

4 Bayesian Estimation

In this section, we estimate σ and χ that are identified as important parameters controlling the reaction of the macroeconomic variables to a monetary policy shock, using a Bayesian approach. We then test whether the non-separable preferences are supported by the data and investigate whether our model actually can explain the sectoral comovement in response to a monetary policy shock.

4.1 Empirical Specification and Data

We consider including the following observables:

$$\pi_{c,t} \equiv \log\left(\frac{P_{c,t}}{P_{c,t-1}}\right) = \text{Nondurable price inflation}$$

$$dc_t \equiv \log\left(\frac{C_t}{C_{t-1}}\right) = \text{Growth rate of per capita nondurable consumption expenditure}$$

$$dx_t \equiv \log\left(\frac{X_t}{X_{t-1}}\right) = \text{Growth rate of per capita durable consumption expenditure}$$

$$dw_t \equiv \log\left(\frac{w_t}{w_{t-1}}\right) = \text{Real wage growth}$$

$$h_t \equiv \text{Log per capita hours worked}$$

$$f\!f_t \equiv \text{Federal funds rate (quarterly rate)}$$

We define nondurable consumption expenditure as the sum of nondurable and services, excluding expenditure on housing and utility. Durables consumption expenditure consists of consumer durable spending, housing and utility expenditure, and residential investment. Based on these definitions, we construct $\pi_{c,t}$, dc_t, and dx_t using data from the NIPA tables.[7]

Ideally, we wish to include the quality-adjusted data on the stock of consumer durable goods as observables in the estimation. However, the quality-adjusted series on consumer durable goods are difficult to measure and the ones constructed by Gordon (1990) are only available up to 1983:Q4. Recently, Cummins and Violante (2002) update the Gordon's quality-adjusted series all the way to 2000 for producer durable goods such as equipment and software, not for consumer durable goods. To get around the problem with the data on the consumer durable stock, we use the expenditure data on consumer durable goods spending (X_t). As pointed out by Guerron-Quintana (2010), a choice of observables could affect the estimation outcomes. However, we think that the use of the flow variable conveys sufficient information on estimating our parameters of interest.

There are four structural shocks in the model (aggregate and sectoral technology shocks, and monetary policy shock). In order to avoid the problem of the stochastic singularity problem, we include measurement errors, as in Sargent (1989). The link between the observables and the model

[7] Details are explained in the Appendix.

variables in the form of the observation equation takes the following form:

$$\pi_{c,t} = \pi_t^c + e_{\pi,t}, \tag{31}$$

$$dc_t = \hat{C}_t - \hat{C}_{t-1} + e_{c,t}, \tag{32}$$

$$dx_t = \hat{X}_t - \hat{X}_{t-1} + e_{x,t}, \tag{33}$$

$$dw_t = \hat{W}_t - \hat{W}_{t-1} + e_{w,t}, \tag{34}$$

$$h_t = \hat{L}_t + e_{h,t}, \tag{35}$$

$$f\!f_t = \hat{R}_t^n, \tag{36}$$

where $\pi_t^c = P_{c,t}/P_{c,t-1}$, and $e_{\pi,t}$, $e_{c,t}$, $e_{x,t}$, $e_{h,t}$, and $e_{w,t}$ are measurement errors associated with durable-price inflation, nondurable expenditure growth, durable expenditure growth, the growth rate of per capita hours worked, the real wage growth, respectively. Note that since we observe the value of the interest rate, no measurement error term is included in (36). Those measurement errors are assumed to be uncorrelated with each other at any lags and leads. Instead of including measurement errors, we could introduce additional structural shocks, such as serially correlated price and wage markup shocks that are considered in Lee (2009). However, for our purpose of testing the non-separability in the environment of Barsky, House, and Kimball (2007), the inclusion of measurement errors would be preferred since it does not alter the model structure in an important way.

The solution to the log-linearized system of equations characterizing the equilibrium conditions in the model are expressed in the form of the first-order difference equations. The first-order difference equations and the observation equations (31)–(36) together form the state-space model that we will estimate with a standard Bayesian approach, which is explained in detail by An and Schorfheide (2007) and Fernández-Villaverde (2009), for example. Some details are outlined in the Appendix. We first numerically find the posterior modes, and the posterior distributions of parameters of our interest are obtained from the random-walk Metropolis-Hastings algorithm. We set the scaling parameter such that the average acceptance rate is about 30%.

We retrieve the effective Federal funds rate (FEDFUNDS), Hours of All Persons (Nonfarm Business Sector, HOANBS), Compensation Per Hour (Nonfarm Business Sector, COMPNFB), GDP deflator (GDPDEF), and Total Population (POP) from FRED of the St. Louis Fed. The monthly Federal Funds rate is converted to quarterly observations by taking the quarterly averages. The annualized percentage Fed funds rate is converted to quarterly rate (decimal number) by dividing it by 400. We deflate the nonfarm business sector compensation per hour by the GDP deflator to get the real wage index. The monthly population data is converted to quarterly by taking the end-of-quarter observations. All of these data are demeaned. The sample starts from 1959:Q2 and ends at 2010:Q4.

Table 1: Parameters and Prior Distribution

Parameter	Description	Distribution	Mean	Std. Dev.
$1/\sigma$	Inverse of intertemporal elasticity of substitution	Normal	1.50	0.37
χ	Curvature of $a(u)$, $\chi \equiv a''(1)/a'(1)$	Inverse Gamma	0.01	2
ρ	Elasticity of substitution between C_t and D_t	Normal	1.17	0.1
ρ_A	Persistence of aggregate productivity shock	Beta	0.5	0.2
ρ_{A_c}	Persistence of nondurable-specific technology shock	Beta	0.5	0.2
ρ_{A_x}	Persistence of durable-specific technology shock	Beta	0.5	0.2
ρ_R	Interest smoothing coefficient in the Taylor rule	Beta	0.75	0.1
ρ_π	Coefficient on the inflation rate in the Taylor rule	Normal	1.5	0.25
ρ_Y	Coefficient on the output gap in the Taylor rule	Normal	0.12	0.05
σ_ξ	Std. Dev. of aggregate technology shock	Inverse Gamma	0.05	2
σ_{ξ_c}	Std. Dev. of sectoral technology shock in nondurable	Inverse Gamma	0.05	2
σ_{ξ_x}	Std. Dev. of sectoral technology shock in durable	Inverse Gamma	0.05	2
σ_{ξ_R}	Std. Dev. of monetary policy shock	Inverse Gamma	0.05	2
σ_{e_π}	Std. Dev. of measurement error for $\pi_{c,t}$	Inverse Gamma	0.05	2
σ_{e_C}	Std. Dev. of measurement error for dc_t	Inverse Gamma	0.05	2
σ_{e_X}	Std. Dev. of measurement error for dx_t	Inverse Gamma	0.05	2
σ_{e_W}	Std. Dev. of measurement error for dw_t	Inverse Gamma	0.05	2
σ_{e_h}	Std. Dev. of measurement error for h_t	Inverse Gamma	0.05	2

4.2 Prior

We impose the following parameter values that are used in Barsky, House, and Kimball (2007), so that our results are comparable to their specification. We set $\beta = 1.02^{-0.25}$ and $\delta = 0.0125$, such that the annual discount rate is 2% and the annual depreciation rate becomes 5% per year. The capital share in the economy α is set to 0.33. We set the Frisch labor supply elasticity to unity. The values of ε_c and ε_x equal to 11, so that the steady-state markup becomes 10% in both nondurable and durable sectors. Finally, setting $\omega_c = 0.75$ results in the nondurable sector accounting for 75% of GDP in a steady state.

Furthermore, we impose the Calvo parameters, such that there are the sticky-price nondurable sector and flexible-price durable sector. Specifically, we set $\theta_c = 2/3$ and $\theta_d = 0$. This corresponds to the case, where the comovement problem arises in Barsky, House, and Kimball (2007). In this sense, the estimated parameter values are conditional on these Calvo parameters.

Parameters to be estimated and the associated prior distributions are summarized in Table 1. The prior distribution for $1/\sigma$, which is an inverse of intertemporal elasticity of substitution, is adapted from Smets and Wouters (2007). The prior mean for χ, which is the curvature parameter for utilization costs, is set to 0.01, which is the value used in Christiano, Eichenbaum, and Evans (2005). The prior mean for ρ, which is the elasticity of substitution between nondurable and durable consumption, is set based on the GMM estimate and the corresponding standard error in Ogaki and Reinhart (1998). Other priors are standard. Priors for the persistence parameter, the Taylor rule coefficients, and standard deviations of the structural shocks are all adapted from Smets and Wouters (2007). We set the priors for the measurement errors to be the same as those for the structural shocks.

Table 2: Posterior Distributions of the Parameters

		Posterior Distributions			
		Non-Separable		*Separable*	
Parameter	Prior Mean	Mean	90% Credible Set	Mean	90% Credible Set
$1/\sigma$	1.500	3.1649	[2.8280, 3.5086]	1	n.a.
χ	0.010	0.0083	[0.0024, 0.0152]	0.0199	[0.0023, 0.0581]
ρ	1.170	1.3491	[1.1924, 1.4947]	1.0359	[0.8315, 1.2635]
ρ_A	0.500	0.9472	[0.9378, 0.9571]	0.9634	[0.9533, 0.9737]
ρ_{A_c}	0.500	0.6415	[0.4941, 0.7896]	0.6616	[0.5127, 0.7991]
ρ_{A_x}	0.500	0.8520	[0.8073, 0.8951]	0.9847	[0.9755, 0.9941]
ρ_R	0.750	0.4027	[0.3195, 0.4829]	0.3147	[0.2477, 0.3785]
ρ_π	1.500	1.6741	[1.4941, 1.8586]	1.1044	[1.0293, 1.1948]
ρ_Y	0.120	0.0116	[0.0053, 0.0178]	0.0028	[−0.0011, 0.0067]
σ_ξ	0.050	0.0084	[0.0075, 0.0093]	0.0071	[0.0060, 0.0081]
σ_{ξ_c}	0.050	0.0077	[0.0065, 0.0090]	0.0088	[0.0069, 0.0106]
σ_{ξ_x}	0.050	0.0099	[0.0086, 0.0113]	0.0095	[0.0078, 0.0111]
σ_{ξ_R}	0.050	0.0060	[0.0059, 0.0061]	0.0060	[0.0059, 0.0061]
σ_{e_π}	0.050	0.0061	[0.0059, 0.0063]	0.0060	[0.0059, 0.0063]
σ_{e_C}	0.050	0.0062	[0.0059, 0.0065]	0.0083	[0.0072, 0.0093]
σ_{e_X}	0.050	0.0479	[0.0429, 0.0528]	0.0581	[0.0521, 0.0639]
σ_{e_h}	0.050	0.0063	[0.0059, 0.0068]	0.0063	[0.0059, 0.0068]
σ_{e_W}	0.050	0.0100	[0.0091, 0.0109]	0.0093	[0.0081, 0.0104]
Log Marginal Densities		3842.1670		3755.2594	

Note: The posterior distributions are obtained using the random walk Metropolis-Hastings algorithm with 300,000 draws (the first 10% of draws are discarded as a burn-in period). We use the modified Harmonic mean estimator of Geweke (1999) to obtain the log marginal density.

4.3 Estimation Results

Posterior Estimates of the Parameters Tables 2 reports the posterior distributions of parameters, which are based on 300,000 draws (the first 10% of draws are discarded) using the random walk Metropolis-Hastings algorithm. The columns under the label of *Non-Separable* show the posterior means and the 90% credible set of parameters in the benchmark case. The columns under the label of *Separable* present the posterior distributions when $\sigma = 1$, which is used in Barsky, House, and Kimball (2007), is imposed.

The posterior mean of $1/\sigma$ is 3.1649. The associated 90% credible set is from 2.8280 to 3.5086. The implied elasticity of intertemporal substitution (σ) is 0.3160. The separable preferences (i.e., $1/\sigma = 1$) are clearly outside the credible set. Thus, the data strongly support the non-separability between consumption and leisure. This finding is in line with earlier studies, such as Basu and Kimball (2002) and Guerron-Quintana (2008). Quantitatively, our estimate of the elasticity of intertemporal substitution is somewhere between 0.5 from the single-equation estimate of Basu and Kimball (2002) and 0.12 of Guerron-Quintana (2008) with the minimum distance estimator. Our estimates are closer to 0.36 obtained in Lopez-Salido and Rabanal (2008) based on the Bayesian estimation of the DSGE model without the rule-of-thumb consumers.

The curvature parameter for $a(u)$ is estimated to be 0.0083 with the non-separable preferences. It is estimated to be 0.0199 with the separable preferences, suggesting that the cost of variable capital utilization is less costly under the separable preferences. The posterior mean of the elasticity of substitution between nondurable and durable consumption with the non-separable preferences is 1.3491 and the corresponding 90% credible set ranges from 1.1924 to 1.4947. This suggests that nondurable and durable are substitutes. In terms of the posterior mean, the model with the separable preferences also supports that they are substitutes. However, the associated 90% credible set is rather wide and the degree of substitutability is somewhat inconclusive. These estimates are in line with those obtained by Ogaki and Reinhart (1998) and Piazzesi, Schneider, and Tuzel (2007). The posterior means suggest that the aggregate technology shock appears to be very persistent. The persistence parameter for the nondurable-sector technology shock is estimated to be much less persistent. The persistence of the durable sector-specific technology changes is estimated to be high under the separable preferences.

The posterior mean of the interest smoothing coefficient (ρ_R) shows less smoothing (0.4027 with the non-separable preferences and 0.3147 under the separable preferences) in the monetary policy rule than typically reported in the literature.

The coefficient on the inflation rate shows a stronger stance to the inflation under the non-separable preferences. The posterior mean decreases from 1.6741 to 1.1044 under the separable preferences. The estimated coefficient on the output gap is smaller in magnitude than those typically reported in the literature. The estimated output gap coefficients (ρ_Y) are small. Especially, the credible set under the separable preferences includes zero.

The posterior means of the standard error of the structural shocks are relatively unaffected by the restriction on preferences. The standard deviations of the measurement errors for nondurable and durable expenditure growth vary when we impose $\sigma = 1$.

Bayesian Model Comparison It is of our interest to examine whether the data support the non-separability or not. By using the Bayes factor, we can formally compare the model with and without the non-separability. The Bayes factor can tell us the strength of evidence provided by the data. As discussed above, the majority of parameters are qualitatively unaffected by the separable preferences.

With the Bayes factor, we can compare the model with the non-separable preferences against the one with the separable preferences. We use the modified Harmonic mean estimator of Geweke (1999) to obtain the log marginal density. The log marginal density of the model with the non-separable preferences is 3842.1670. On the other hand, the one associated with the separable preferences is 3755.2594. In order to choose the separable preferences over the non-separable preferences, we need a prior probability of the separable preferences $\exp(86.9076) \approx 5.5 \times 10^{37}$ times larger than that over the non-separable preferences. This difference seems to be overwhelmingly large and suggests that the data decisively support the non-separable preferences.

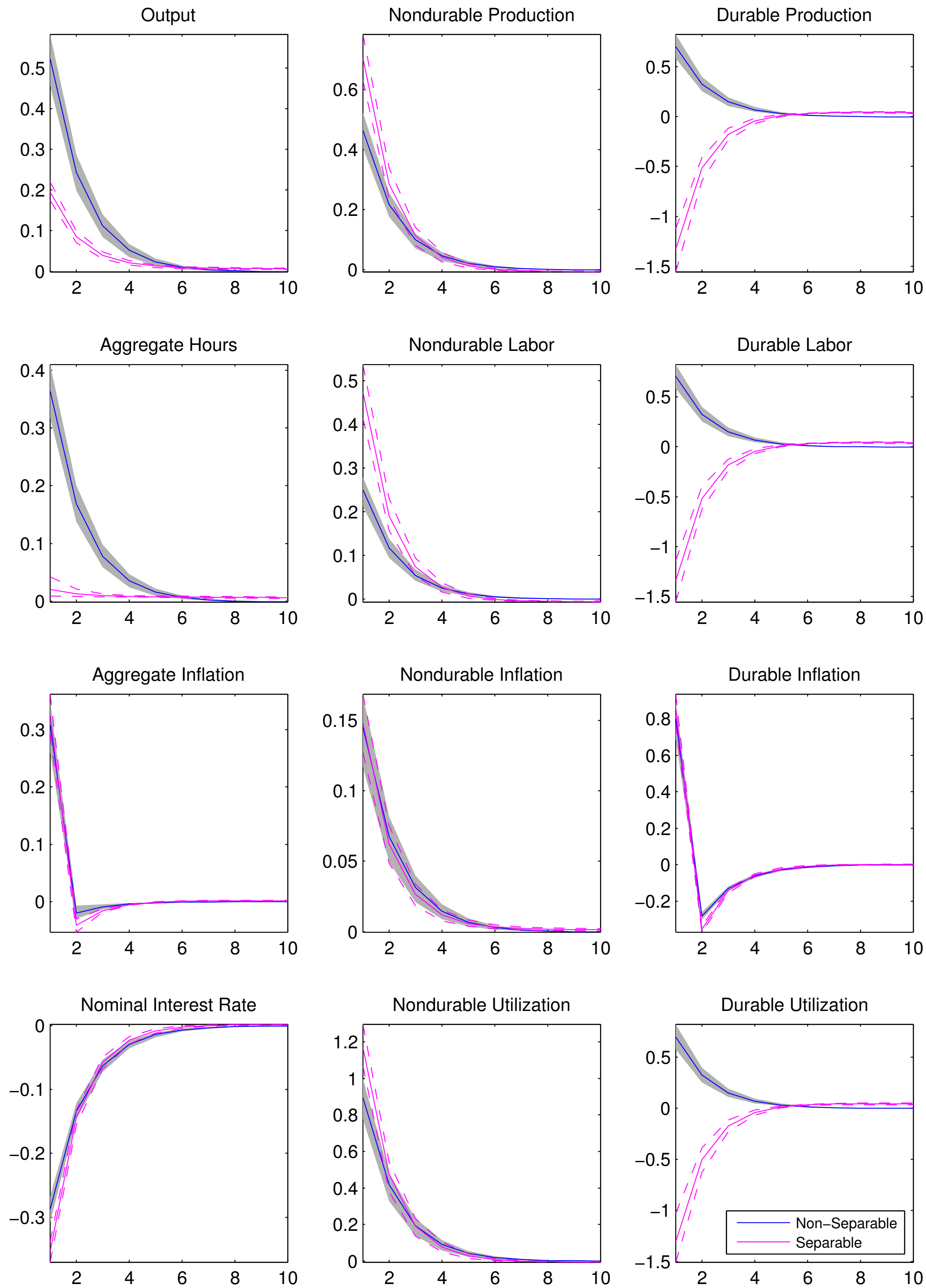

Figure 1: Responses to the Monetary Policy Shock

Note: The horizontal axes take the quarters after the shock and the vertical axes measure percentage deviations from the steady state. The above figures depict the responses of the economy to the one standard-deviation monetary policy shock. The solid lines represent the posterior mean responses, and the shaded areas (or dashed lines for the separable case) correspond to the 5% and 95% posterior intervals.

Impulse Response Functions Figure 1 plots the estimated responses to the expansionary monetary policy shock (i.e., one standard deviation decrease in the interest rate) with and without the non-separability. Solid lines represent the posterior mean responses and the shaded areas (dashed lines for the separable preferences) correspond to the 5% and 95% posterior intervals. The impulse responses are tightly estimated. With the separable preferences, the model exhibits the sectoral comovement problem. Following the shock, there is a large contraction of the production of durable goods, whereas the production of nondurable goods expands. Labor in each sector moves in the opposite direction, leaving aggregate hours worked virtually unchanged.

As our previous analytical results show, however, the figure clearly shows that the model with the non-separable preferences drastically changes the reaction of the macroeconomic variables. Importantly, our estimated degree of the non-separability is indeed strong enough to enable the model to produce a sectoral comovement in response to a monetary shock. Output, hours worked, capital utilization in each sector increase all together following a monetary expansion!

Robustness Thus far, our empirical evidence supporting the non-separable preferences is based upon our maintained assumption from Barsky, House, and Kimball (2007) that firms in the durable sector are flexible to adjust their prices and that the nondurable goods sector has sizable price rigidity (i.e., $\theta_c = 2/3$ and $\theta_d = 0$). One might suspect that our estimates are subject to this particular choice of the Calvo parameters. To show that the non-separability is generally supported by the data, we re-estimate our model without imposing the values for the Calvo parameters. Our prior for the Calvo parameters is based on Beta distribution with mean 0.5 and standard deviation of 0.1, which is adapted from Smets and Wouters (2007).

Table 3 shows the resulting posterior distributions. Quantitatively speaking, results are similar to the case when we impose $\theta_c = 2/3$ and $\theta_d = 0$. The implied elasticity of intertemporal substitution is 0.3275 and the separable preferences are clearly outside the credible set. As before, the Bayes factor also favors the model with non-separable preferences. Therefore, the empirical evidence favoring the non-separability in the utility function is robust to variations in the degree of price flexibility.

5 Conclusion

In the data, strong procyclical fluctuations in the production of durable goods are the most prominent feature of the response to monetary shocks. This paper investigates the role of preferences in matching this feature of the data in a sticky price model with flexibly priced durables. The separability between aggregate consumption and labor supply plays an important role in shaping the reaction of durable goods production. When preferences are separable in aggregate consumption and labor, the model exhibits counterfactual behavior. Flexibly priced durable goods production contracts substantially following a monetary expansion if preferences are separable.

In contrast, the sticky price model with non-separable preferences can replicate the empirically

Table 3: Posterior Distributions of the Parameters with the Estimated Calvo Parameters

		Posterior Distributions			
		Non-Separable		*Separable*	
Parameter	Prior Mean	Mean	90% Credible Set	Mean	90% Credible Set
$1/\sigma$	1.500	3.0536	[2.6926, 3.3922]	1	n.a.
χ	0.010	0.0072	[0.0025, 0.0136]	0.0079	[0.0022, 0.0148]
ρ	1.170	1.3509	[1.2024, 1.4951]	1.1856	[1.0416, 1.3371]
θ_c	0.500	0.5077	[0.4263, 0.5828]	0.4180	[0.3292, 0.4983]
θ_d	0.500	0.1910	[0.1435, 0.2396]	0.2011	[0.1684, 0.2337]
ρ_A	0.500	0.9463	[0.9375, 0.9554]	0.9668	[0.9597, 0.9733]
ρ_{A_c}	0.500	0.4105	[0.2032, 0.6074]	0.7333	[0.6640, 0.8028]
ρ_{A_x}	0.500	0.8350	[0.7905, 0.8836]	0.9902	[0.9882, 0.9928]
ρ_R	0.750	0.3043	[0.2132, 0.3880]	0.2352	[0.1784, 0.2942]
ρ_π	1.500	1.7415	[1.5593, 1.9221]	1.2079	[1.1761, 1.2353]
ρ_Y	0.120	0.0113	[0.0050, 0.0173]	0.0026	[0.0013, 0.0037]
σ_ξ	0.050	0.0090	[0.0080, 0.0099]	0.0085	[0.0075, 0.0094]
σ_{ξ_c}	0.050	0.0067	[0.0059, 0.0074]	0.0067	[0.0059, 0.0075]
σ_{ξ_x}	0.050	0.0099	[0.0085, 0.0113]	0.0082	[0.0071, 0.0094]
σ_{ξ_R}	0.050	0.0061	[0.0059, 0.0064]	0.0061	[0.0059, 0.0063]
σ_{e_π}	0.050	0.0061	[0.0059, 0.0064]	0.0061	[0.0059, 0.0063]
σ_{e_C}	0.050	0.0062	[0.0059, 0.0066]	0.0072	[0.0063, 0.0082]
σ_{e_X}	0.050	0.0498	[0.0450, 0.0547]	0.0569	[0.0516, 0.0622]
σ_{e_h}	0.050	0.0063	[0.0059, 0.0068]	0.0064	[0.0059, 0.0071]
σ_{e_W}	0.050	0.0103	[0.0094, 0.0113]	0.0101	[0.0091, 0.0112]
Log Marginal Densities		3834.6675		3754.5540	

Note: The posterior distributions are obtained using the random walk Metropolis-Hastings algorithm with 300,000 draws (the first 10% of draws are discarded as a burn-in period). We use the modified Harmonic mean estimator of Geweke (1999) to obtain the log marginal density. The prior distributions used are the same as in Table 1. In addition, we use Beta distribution with mean 0.5 and standard deviation 0.1 for θ_c and θ_x.

plausible response of durable goods spending to a monetary expansion. The key to the model's success is due to the fact that non-separable preferences imply the complementarity between non-durable consumption and labor supply, which is absent in separable preferences.

Further, this paper provides additional empirical support for the non-separable preferences, which had been previously shown by Basu and Kimball (2002), Guerron-Quintana (2008), and Lopez-Salido and Rabanal (2008). Contrary to previous studies, our model incorporates durable consumption. We find that even when the durable expenditure is explicitly included in the estimation, the data still support the non-separable preferences. Our estimate for the intertemporal elasticity of substitution is well below the threshold level needed for the sticky price model to produce a strong procyclical response of durable goods spending to an expansionary monetary policy shock. As a result, the estimated degree of non-separability resolves the comovement problem in the sticky price model with flexibly priced durable goods.

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Appendix

Data Construction

We need to construct the following variables:

$$\begin{aligned} C_t &= \text{real expenditure on nondurable and services,} \\ X_t &= \text{real expenditure on durable consumption and residential investment,} \\ \pi_{c,t} &= \text{nondurable consumption price inflation.} \end{aligned}$$

In order to construct C_t and X_t, we need to have nominal consumption expenditures on various consumption goods from the NIPA Table 2.3.5 and corresponding price indices from the NIPA Table 2.3.4. Also, nominal residential investment and the associate price index are obtained from the NIPA Table 5.3.5 and Table 5.3.4, respectively.

One problem is that we cannot add or subtract the levels of chain aggregated price or quantity index.

We want to exclude expenditure on housing services from C_t and include it in X_t. Nominal nondurable consumption expenditure is given by

$$\begin{aligned} TC_t &= P_{c,t}C_t \\ &= \text{Nondurable expenditure} + \text{Expenditure on services} - \text{Expenditure on housing and utilities} \\ &= (\text{line 8 in Table 2.3.5}) + (\text{line 13 in Table 2.3.5}) - (\text{line 15 in Table 2.3.5}) \end{aligned}$$

Note that it seems that there are changes in the classification of categories. Line 15 now includes expenditure on housing services together with utility. Also, line 15 is only available from 1959:Q1, which may constrain our sample size.

We need to construct $P_{c,t}$ by using the Trönqvist index. However, one thing we need to be careful about is that we do not want to include the price index for housing services. In general, the formula for the Törnqvist index aggregating $y_1, \cdots, y_n$ is given by

$$\Delta \ln(Y_t) = \sum_{i=1}^{n} \bar{\omega}_{i,t} \Delta \ln(y_{i,t}), \tag{37}$$

where $\bar{\omega}_{i,t}$ is the aggregating weight on each component and given by

$$\bar{\omega}_{i,t} = \frac{1}{2}(\omega_{i,t} + \omega_{i,t-1}), \tag{38}$$

and $\omega_{i,t}$ is the expenditure share of the category i, such that

$$\omega_{i,t} = \frac{p_{i,t}q_i}{\sum_{i=1}^{n} p_{i,t}q_i}. \tag{39}$$

To be concrete, let us suppose that we need to construct an aggregate price index of nondurable consumption (ND) and services (S), excluding housing services (s_1), which is a subcategory of services. Basic strategy is as follows:

(i) Construct an index Z that aggregates ND and S.

(ii) Then, construct the index of our interest C by using Z and s_1.

The first step is just applying the formula (37) to create new aggregate Z. We calculate

$$\Delta \ln(Z_t) = \frac{1}{2}(\omega_{ND,t} + \omega_{ND,t-1})\Delta \ln(ND_t) + \frac{1}{2}(\omega_{S,t} + \omega_{S,t-1})\Delta \ln(S_t), \tag{40}$$

where $\omega_{ND,t} = \dfrac{P_{ND,t}ND_t}{(P_{ND,t}ND_t + P_{S,t}S_t)}$ and $\omega_{S,t} = 1 - \omega_{ND,t}$.

The second step is to recognize that the index Z consists of s_1 and C, so that we have

$$\Delta \ln(Z_t) = \frac{1}{2}(\omega_{s_1,t} + \omega_{s_1,t-1})\Delta \ln(s_{1,t}) + \frac{1}{2}(\omega_{C,t} + \omega_{C,t-1})\Delta \ln(C_t), \tag{41}$$

where $\omega_{C,t} = 1 - \omega_{s_1,t}$. Here $\omega_{s_1,t} = \frac{P_{s_1,t}s_{1,t}}{P_{z,t}Z_t}$.

Thus, we can calculate the index of our interest C_t as follows:

$$\Delta \ln(C_t) = \frac{2}{(2 - \omega_{s_1,t} - \omega_{s_1,t-1})}\left\{\Delta \ln(Z_t) - \frac{1}{2}(\omega_{s_1,t} + \omega_{s_1,t-1})\Delta \ln(s_{1,t})\right\} \tag{42}$$

and use these growth rates to uncover the level of the variable.

We can also construct X_t in a similar fashion. The total expenditure on X_t is defined as follows:

$$\begin{aligned} TX_t &= P_{x,t}X_t \\ &= \text{Durable expenditure} + \text{Expenditure on housing and utilities} + \text{Residential investment} \\ &= (\text{line 3 in Table 2.3.5}) + (\text{line 15 in Table 2.3.5}) + (\text{line 17 in Table 5.3.5}) \end{aligned}$$

Estimation Details

Let $\boldsymbol{\theta}$ denote a vector of parameters to be estimated and use $p(\boldsymbol{\theta})$ to denote the prior distribution of the parameter vector. $p(\mathcal{Y}_T; \boldsymbol{\theta})$ represents the likelihood of the data given the parameter $\boldsymbol{\theta}$, where $\mathcal{Y}_t$ stacks all observations as $\mathcal{Y}_T = [\boldsymbol{y}_1, \cdots, \boldsymbol{y}_T]$ and $\boldsymbol{y}_t$ is a vector of observables at time t.

By the Bayes rule, the posterior distribution of $\boldsymbol{\theta}$ is given by

$$p(\boldsymbol{\theta}|\mathcal{Y}_T) = \frac{p(\mathcal{Y}_T|\boldsymbol{\theta})p(\boldsymbol{\theta})}{p(\mathcal{Y}_T)}. \tag{43}$$

All results reported in the paper are based on 300,000 draws from the posterior distribution

$p(\boldsymbol{\theta}|\mathcal{Y}_T)$, which are generated from the random walk Metropolis-Hastings algorithm. Note that the first 30,000 draws are discarded as a burn-in period. The posterior mode and the associated variance-covariance matrix are used to configure a starting point for the random walk Metropolis-Hastings algorithm.

Using the state-space representation of the model and the Kalman filter, we can easily evaluate the log-likelihood, $\log p(\mathcal{Y}_T|\boldsymbol{\theta})$. We numerically maximize the log posterior kernel, $\log p(\mathcal{Y}_T|\boldsymbol{\theta}) + \log p(\boldsymbol{\theta})$, with respect to $\boldsymbol{\theta}$ in order to find the posterior mode. The initial mean of jumping distribution is set at the posterior mode, and the variance-covariance matrix is set to the inverse of the Hessian evaluated at the posterior mode.

At the i^{th} Metropolis-Hastings draw, a candidate parameter vector $\boldsymbol{\theta}^*$ is drawn from $N(\boldsymbol{\theta}^{(i-1)}, c\boldsymbol{\Sigma})$, where c is a scaling factor and $\boldsymbol{\Sigma}$ is the inverse of the Hessian at the posterior mode. Then we compute the acceptance ratio

$$r = \frac{p(\boldsymbol{\theta}^*|\mathcal{Y}_T)}{p(\boldsymbol{\theta}^{(i-1)}|\mathcal{Y}_T)} = \frac{p(\mathcal{Y}_T|\boldsymbol{\theta}^*)p(\boldsymbol{\theta})}{p(\mathcal{Y}_T)} p(\mathcal{Y}_T|\boldsymbol{\theta}^{(i-1)})p(\boldsymbol{\theta})p(\mathcal{Y}_T) \tag{44}$$

and we accept $\boldsymbol{\theta}^*$ and set $\boldsymbol{\theta}^{(i)} = \boldsymbol{\theta}^*$ with probability $\min(r, 1)$ and reject otherwise (i.e., $\boldsymbol{\theta}^{(i)} = \boldsymbol{\theta}^{(i-1)}$). The scaling factor c is set, such that the fraction of candidate draws that are accepted becomes about 30%.

Given two specifications $\mathcal{M}_1$ and $\mathcal{M}_2$, the posterior odds ratio is given by

$$\frac{p(\mathcal{M}_1|\mathcal{Y}_T)}{p(\mathcal{M}_2|\mathcal{Y}_T)} = \underbrace{\frac{p(\mathcal{M}_1)}{p(\mathcal{M}_2)}}_{\text{Prior odds}} \underbrace{\frac{p(\mathcal{Y}_T|\mathcal{M}_1)}{p(\mathcal{Y}_T|\mathcal{M}_2)}}_{\text{Bayes factor}}. \tag{45}$$

For the Bayesian model comparison, we need to compute the marginal data density, $p(\mathcal{Y}_T|\mathcal{M}_j)$ for $j = 1, 2$, which is difficult to evaluate. Geweke (1999) proposes to use the following estimator

$$\hat{p}(\mathcal{Y}_T|\mathcal{M}_j) = \left[\frac{1}{K}\sum_{k=1}^{K} \frac{f(\boldsymbol{\theta}_j^{(k)})}{p(\mathcal{Y}_T|\boldsymbol{\theta}_j^{(k)}, \mathcal{M}_j)p(\boldsymbol{\theta}_j^{(k)}|\mathcal{M}_j)}\right]^{-1}, \tag{46}$$

where $\boldsymbol{\theta}_j^{(k)}$ is a Metropolis-Hastings draw from $p(\boldsymbol{\theta}|\mathcal{Y}_T, \mathcal{M}_j)$ and K is the number of the Metropolis-Hastings draws. $f(\boldsymbol{\theta})$ is specified as the density of a truncated multivariate normal distribution,

$$f(\boldsymbol{\theta}) = \tau^{-1}(2\pi)^{-\frac{d}{2}} |\boldsymbol{V_\theta}|^{-\frac{1}{2}} \exp\left[-\frac{1}{2}(\boldsymbol{\theta} - \bar{\boldsymbol{\theta}})'(\boldsymbol{V_\theta})^{-1}(\boldsymbol{\theta} - \bar{\boldsymbol{\theta}})\right] \times \mathbb{1}\left\{(\boldsymbol{\theta} - \bar{\boldsymbol{\theta}})'\boldsymbol{V_\theta}^{-1}(\boldsymbol{\theta} - \bar{\boldsymbol{\theta}}) \leq F_{\chi_d^2}^{-1}(\tau)\right\}, \tag{47}$$

where $\bar{\boldsymbol{\theta}}$ and $\boldsymbol{V_\theta}$ are the posterior mean and variance-covariance matrix computed from the Metropolis-Hastings algorithm, d is the size of $\boldsymbol{\theta}$, $F_{\chi_d^2}$ is the cumulative density function of a χ^2 random variable with d degrees of freedom, $\tau \in (0, 1)$, and $\mathbb{1}\{\cdot\}$ is an indicator fuction.