

The Transmission of Monetary Policy in a Multi-Sector Economy*

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Abstract

This paper constructs and estimates a sticky-price, Dynamic Stochastic General Equilibrium model with heterogeneous production sectors. Firms in different sectors vary in their price rigidity, production technology, and the combination of material and investment inputs. In particular, firms buy inputs from all sectors using the actual Input-Output Matrix and Capital Flow Table of the U.S. economy. By relaxing the standard assumption of symmetry, this model allows idiosyncratic sectoral dynamics in response to monetary policy shocks. The model is estimated by the Generalized Method of Moments using sectoral and aggregate U.S. time series. Econometric results indicate 1) heterogeneity in price rigidity across sectors, with services by far the most price-rigid sector in the U.S. economy; 2) a strong sensitivity to monetary policy shocks on the part of construction and durable manufacturing despite the fact that their prices are flexible; and 3) more persistent monetary policy effects in the multi-sector economy compared with its symmetric counterpart.

JEL Classification: E3, E4, E5

Key Words: Multi-sector models, sticky-price DGSE models, monetary policy

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1 Introduction

Economies involve the production and exchange of different goods produced in different sectors using distinct technologies and inputs. However, this heterogeneity is only partly acknowledged in the sticky-price Dynamic Stochastic General Equilibrium (DSGE) models which have become the main tool of monetary policy analysis.¹ Those models assume that goods are different enough to confer the producer a degree of monopoly power, but in the symmetric equilibrium all relative prices are equal to one and allocations are identical across sectors. This approach simplifies aggregation, but it also means that the models cannot address some important questions in monetary economics such as why monetary disturbances appear to have larger effects in some sectors of the economy than in others, and how heterogeneity in price rigidity across goods affects the transmission of monetary policy.

This paper constructs and estimates a sticky-price DSGE model where a finite number of productive sectors are heterogenous in price rigidity, production function parameters, and the combination of goods used as material and investment inputs. Within each sector, there is a continuum of monopolistically competitive firms that produce differentiated goods but are identical otherwise. Firms in different sectors use productive factors in different intensities and buy material and investment inputs from all sectors following the actual Input-Output Matrix and Capital Flow Table of the U.S. economy. For empirical purposes, this paper concentrates on six broad sectors, namely agriculture, mining, construction, durable and nondurable manufacturing, and services, that roughly correspond to the Division level of the Standard Industry Classification (SIC). The model is estimated by the Generalized Method of Moments (GMM) using a mixture of aggregate and sectoral U.S. time series.

Econometric results show that there is heterogeneity in price rigidity across sectors. This heterogeneity is statistically significant and quantitatively important. More precisely, the hypothesis that price rigidity is the same in all sectors is rejected by the data. Also, while the hypothesis that prices are flexible cannot be rejected for durable and primary goods, it can be rejected for services and nondurable manufactured goods. GMM estimates indicate that price rigidity is by far the largest in the service sector. Because services receive a large weight in the Consumer Price Index (CPI), our results suggest that previous estimates of aggregate price rigidity are mainly driven by price rigidity in services.

Our results are consistent with those reported by micro studies based on final goods that

¹See, among many others, Blanchard and Kiyotaki (1987), Yun (1996), Rotemberg and Woodford (1997), Chari, Kehoe and McGrattan (2000), Kim (2000), Ireland (2001, 2003), Bouakez, Cardia and Ruge-Murcia (2005a), and Christiano, Eichenbaum and Evans (2005).

enter the CPI (see, among others, Bils and Klenow, 2004, and Nakamura and Steinsson, 2007) which find heterogeneous price stickiness and less frequent price adjustments for services than for goods. We derive the price durations implied by our estimates and compare them with duration estimates computed from the micro data. In spite of the large methodological difference between these two approaches, estimates are remarkably similar for comparable sectors. However, the one exception is services, for which our estimates imply longer duration than most of the previous micro studies. We provide suggestive evidence that this result is due to the fact that most micro studies abstract from actual and imputed residential rents, which are among the most rigid prices in the economy. In particular, the German study by Hoffmann and Kurz-Kim (2004), which includes actual apartment rents, delivers a duration estimate for service prices that is very close to ours. Moreover Hoffmann and Kurz-Kim also report that the exclusion of rents from their sample reduces the overall duration of price spells from 21 to 16 months. This suggests that abstracting from rents may bias downwards estimates of aggregate price rigidity based on micro data.

Impulse-response analysis indicates that there is substantial heterogeneity in the sectoral effects of monetary policy shocks and positive output comovement across sectors. Output in services and construction increase by more than in durable and nondurable manufacturing, which in turn increase by more than in the primary sectors. However, the mechanisms by which these responses take place are different. The response of services and nondurable manufacturing reflects the partial accommodation of a demand increase by the monopolistically competitive producer of a sticky-price good. The response of construction and durable manufacturing is due to the increase in demand for investment goods by other sectors. Although prices in agriculture and mining are flexible and these sectors do not produce capital goods, their output increases because they produce material inputs employed by the other sectors. Similar results where output responses to monetary policy shocks are positively correlated across sectors and are large on the part of durable-good producers are also documented by the vector autoregressions (VAR) in Barth and Ramey (2001), Dedola and Lippi (2005), and Peersman and Smets (2005). However, in general, VAR analysis does not reveal the economic mechanism by which heterogenous sectoral responses arise. In contrast, the fully-specified DSGE model developed here reveals that the output effects of a monetary policy shock arise from price stickiness in part of the economy and are transmitted to the rest via the input-output structure.

Finally, comparing the aggregate predictions of the multi-sector model and its symmetric counterpart indicates that production heterogeneity amplifies the propagation mechanism of the model and delivers additional persistence in response to monetary disturbances.

The paper is organized as follows. Section 2 constructs a monetary model with hetero-

geneous production sectors. Section 3 describes the data and the econometric methodology, reports parameter estimates, and studies the properties of the estimated model. Finally, Section 4 concludes.

2 The Model

The economy consists of identical infinitely-lived households, a government, and J distinct production sectors. Sectors are heterogeneous in their production function parameters, price stickiness and the combination of goods used as material and investment inputs. Within each sector, there is a continuum of monopolistically competitive firms which produce differentiated goods but are identical otherwise. We will see below that this market structure delivers an equilibrium which is symmetric within sectors but asymmetric between sectors.

2.1 Households

The representative household maximizes

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{t-\tau} (\log(C_t) + \log(M_t/P_t) + \eta_t \log(1 - N_t)), \quad (1)$$

where $\beta \in (0, 1)$ is the subjective discount factor, C_t is consumption, M_t is the nominal money stock, P_t is an aggregate price index, N_t is hours worked and η_t is an aggregate preference shock. Since the total time endowment is normalized to one, $1 - N_t$ represents leisure time. The functional form of the instantaneous utility is motivated by theoretical results in Ngai and Pissarides (2007) who show that necessary and sufficient conditions for the existence of an aggregate balanced growth path in a multi-sector economy are logarithmic preferences and a non-unit price elasticity of demand. The population size is constant and normalized to one.

Consumption is an aggregate over all available goods:

$$C_t = \prod_{j=1}^J (\xi^j)^{-\xi^j} (c_t^j)^{\xi^j}, \quad (2)$$

where c_t^j is the household's consumption of goods produced in sector j and $\xi^j \in [0, 1]$ are weights that satisfy $\sum_{j=1}^J \xi^j = 1$. In turn, c_t^j is

$$c_t^j = \left(\int_0^1 (c_t^{lj})^{(\theta-1)/\theta} dl \right)^{\theta/(\theta-1)}, \quad (3)$$

where c_t^{lj} is the household's consumption of the good produced by firm l in sector j and $\theta > 1$ is the elasticity of substitution between goods produced in the same sector. The Cobb-Douglas function in (2) is a special case of the CES (Constant Elasticity of Substitution) aggregator where the elasticity of substitution tends to one. This function has two desirable implications. First, the weights ξ^j are equal to the household's sectoral expenditures shares, which can be computed using data from the National Income and Product Accounts (NIPA). Second, goods produced in the same sector (say, apples and oranges) are better consumption substitutes than goods produced in different sectors (say, apples and hammers).

The aggregate price index P_t is defined as

$$P_t = \prod_{j=1}^J (p_t^j)^{\xi^j}, \quad (4)$$

where

$$p_t^j = \left(\int_0^1 (p_t^{lj})^{1-\theta} dl \right)^{1/(1-\theta)} \quad (5)$$

and p_t^{lj} is the price of the good produced by firm l in sector j . Because P_t is the price index associated with the bundle of goods consumed by households, it may be interpreted as the Consumer Price Index (CPI) in our model economy.

The household's labor supply is an aggregate of the hours they supply to each firm in each sector. That is,

$$N_t = \left(\sum_{j=1}^J (n_t^j)^{(\varsigma+1)/\varsigma} \right)^{\varsigma/(\varsigma+1)}, \quad (6)$$

where $\varsigma > 0$ is a constant parameter that determines the elasticity of substitution between sectoral hours and n_t^j is the number of hours worked in sector j . In turn,

$$n_t^j = \int_0^1 n_t^{lj} dl, \quad (7)$$

where n_t^{lj} is the number of hours worked in firm l in sector j . The aggregator (6) allows heterogeneity in sectoral variables while preserving the tractable representative-agent framework. In particular, (6) implies limited labor mobility across sectors and, consequently, wages and hours will be different in different sectors. On the other hand, the aggregator (7) implies that hours worked in different firms in the same sector are perfect substitutes and labor is perfectly mobile within sectors. As a result, wages and hours will be the same for all firms in the same sector. The assumption that the cross-sectional dispersion of wages and hours is larger across, than within, sectors is consistent with empirical evidence reported by Davis and Haltiwanger (1991).

There are $J + 2$ financial assets in this economy: money, a one-period interest-bearing nominal bond, and shares in a mutual fund for each of the J productive sectors. The household enters period t with M_{t-1} units of currency, B_{t-1} nominal private bonds, and s_{t-1}^j shares in mutual fund $j = 1, \dots, J$, and then receives interests, dividends, wages and a lump-sum transfer from the government. These resources are used to finance consumption and the acquisition of financial assets to be carried over to next period. Expressed in real terms, the household's dynamic budget constraint is

$$\begin{aligned} \sum_{j=1}^J \int_0^1 \left(\frac{p_t^{lj} c_t^{lj}}{P_t} \right) dl + b_t + m_t + \sum_{j=1}^J \int_0^1 \left(\frac{a_t^{lj} s_t^{lj}}{P_t} \right) dl &= \sum_{j=1}^J \int_0^1 \left(\frac{w_t^{lj} n_t^{lj}}{P_t} \right) dl + \frac{R_{t-1} b_{t-1}}{\pi_t} + \frac{m_{t-1}}{\pi_t} \\ &+ \sum_{j=1}^J \int_0^1 \left(\frac{(d_t^{lj} + a_t^{lj}) s_{t-1}^{lj}}{P_t} \right) dl + \frac{\Upsilon_t}{P_t}, \end{aligned}$$

where $b_t = B_t/P_t$ is the real value of nominal bond holdings, $m_t = M_t/P_t$ is real money balances, w_t^{lj} is the nominal wage paid by firm l in sector j , R_t is the gross nominal interest rate on bonds that mature at time $t + 1$, π_t is the gross inflation rate between periods $t - 1$ and t , Υ_t is a government lump-sum transfer, and a_t^j and d_t^j are, respectively, the price of a share in, and the dividend paid by, mutual fund j .

The household's utility maximization is carried out by choosing optimal sequences $\{c_t^{lj}, n_t^{lj}, M_t, B_t, s_t^j\}_{t=\tau}^\infty$ subject to the sequence of dynamic budget constraints, a no-Ponzi-game condition, and initial asset holdings. The first-order conditions for this problem determine the consumption demand for each good, labor supplied to each firm and money demand, and price the nominal bond and the shares in each sector. In particular, the consumption demand for the good produced by firm l in sector j is

$$c_t^{lj} = \xi^j \left(\frac{p_t^{lj}}{p_t^j} \right)^{-\theta} \left(\frac{p_t^j}{P_t} \right)^{-1} C_t. \quad (8)$$

Using this demand function and the definition of the price indices, it is easy to show that $\sum_{j=1}^J \int_0^1 p_t^{lj} c_t^{lj} dl = \sum_{j=1}^J p_t^j C_t^j = P_t C_t$.

2.2 Firms

The representative firm l in sector j uses the technology,

$$y_t^{lj} = (z_t^j n_t^{lj})^{\nu^j} (k_t^{lj})^{\alpha^j} (H_t^{lj})^{\gamma^j}, \quad (9)$$

where y_t^{lj} is output, z_t^j is a sector-specific productivity shock, k_t^{lj} is capital, H_t^{lj} is material inputs, and the parameters $\nu^j, \alpha^j, \gamma^j \in (0, 1)$ and satisfy the linear restriction $\nu^j + \alpha^j + \gamma^j = 1$.

Material inputs are combined according to

$$H_t^{lj} = \prod_{i=1}^J \zeta_{ij}^{-\zeta_{ij}} (h_{i,t}^{lj})^{\zeta_{ij}}, \quad (10)$$

where

$$h_{i,t}^{lj} = \left(\int_0^1 (h_{mi,t}^{lj})^{(\theta-1)/\theta} dm \right)^{\theta/(\theta-1)}, \quad (11)$$

$h_{mi,t}^{lj}$ is the quantity of input produced by firm m in sector i that is purchased by firm l in sector j , and the weights ζ_{ij} satisfy $\zeta_{ij} \in [0, 1]$ and $\sum_{i=1}^J \zeta_{ij} = 1$. This specification represents the fact that, in actual economies, different goods are produced using different materials mixed in different proportions.² The price of the composite good H_t^j is

$$Q_t^{H^j} = \prod_{i=1}^J (p_t^i)^{\zeta_{ij}}. \quad (12)$$

Firms own directly their capital stock. The stock of capital follows the law of motion

$$k_{t+1}^{lj} = (1 - \delta)k_t^{lj} + X_t^{lj}, \quad (13)$$

where δ is the rate of depreciation and X_t^{lj} is an investment technology that aggregates different goods into additional units of capital. Specifically,

$$X_t^{lj} = \prod_{i=1}^J \kappa_{ij}^{-\kappa_{ij}} (x_{i,t}^{lj})^{\kappa_{ij}}, \quad (14)$$

where

$$x_{i,t}^{lj} = \left(\int_0^1 (x_{mi,t}^{lj})^{(\theta-1)/\theta} dm \right)^{\theta/(\theta-1)}, \quad (15)$$

$x_{mi,t}^{lj}$ is the quantity of good produced by firm m in sector i that is purchased by firm l in sector j for investment purposes, and the weights κ_{ij} satisfy $\kappa_{ij} \in [0, 1]$ and $\sum_{i=1}^J \kappa_{ij} = 1$. The Cobb-Douglas functions in (10) and (14) imply that the weights ζ_{ij} and κ_{ij} are respectively equal to the share of sector i in the material and investment input expenditures by sector j . In the empirical section of the paper, these shares are computed using data from the Use

²Our production structure is of a roundabout type meaning that any good (including capital goods) may be generally used to produce any other good. For example, iron ore is used to produce steel and tools, but tools are used to dig for ore. Basu (1995) uses this structure to study how material inputs can magnify price stickiness and contribute to the persistence of monetary shocks. As an alternative, chain-of-production models assume that a good (say, an intermediate good) may be used in the production of another one (a final good), but the converse is not true. These structure has been used to study similar issues by, among others, by Huang and Liu (2001, 2007).

and the Capital Flow Tables of the U.S. Input-Output accounts. The price of the composite investment good X_t^j is

$$Q_t^{X^j} = \prod_{i=1}^J (p_t^i)^{\kappa_{ij}}. \quad (16)$$

Adjusting the capital stock is assumed to involve a quadratic cost that is proportional to the current capital stock,

$$\Gamma_t^{lj} = \Gamma(X_t^{lj}, k_t^{lj}) = \frac{\chi}{2} \left(\frac{X_t^{lj}}{k_t^{lj}} - \delta \right)^2 k_t^{lj}, \quad (17)$$

where χ is a nonnegative parameter.

This specification allows firms in each sector to combine different proportions of investment goods to accumulate a stock of capital that is sector specific. Note, however, that the specificity of capital here is different from that in Woodford (2005) and Altig, Christiano, Eichenbaum and Linde (2005). In those models, firms accumulate a form of capital that is not transferable to other firms. In our model, capital is firm specific only in the sense that the nonlinear combination of investment inputs may be different across firms. However, the composite X_t^{lj} can be unbundled and its parts sold to other firms in a market subject to the adjustment costs described by Equation (17).

Nominal prices are sticky because firms face a convex real per-unit cost when changing their price. This cost is represented by the quadratic form (Rotemberg, 1982),

$$\Phi_t^{lj} = \Phi(p_t^{lj}, p_{t-1}^{lj}) = \frac{\phi^j}{2} \left(\frac{p_t^{lj}}{\pi_{ss} p_{t-1}^{lj}} - 1 \right)^2, \quad (18)$$

where $\phi^j \geq 0$ and π_{ss} is the steady-state rate of inflation. In the special case where $\phi^j = 0$ the prices of goods produced in sector j are flexible. Since the price elasticity of demand does not depend on the use given to the good by the buyer, producers will charge the same price to firms in all sectors and to households regardless of whether their output is employed as investment good, consumption good, or material input.³

The nominal profits of firm l in sector j , which will be transferred to shareholders in the form of dividends, are

$$\begin{aligned} d_t^{lj} = & p_t^{lj} \left(c_t^{lj} + \sum_{i=1}^J \int_0^1 x_{lj,t}^{mi} dm + \sum_{i=1}^J \int_0^1 h_{lj,t}^{mi} dm \right) - w_t^{lj} n_t^{lj} - \sum_{i=1}^J \int_0^1 p_t^{mi} x_{mi,t}^{lj} dm - \sum_{i=1}^J \int_0^1 p_t^{mi} h_{mi,t}^{lj} dm \\ & - \Gamma_t^{lj} Q_t^{X^j} - \Phi_t^{lj} p_t^{lj} \left(c_t^{lj} + \sum_{i=1}^J \int_0^1 x_{lj,t}^{mi} dm + \sum_{i=1}^J \int_0^1 h_{lj,t}^{mi} dm \right), \end{aligned} \quad (19)$$

³By allowing different elasticities of substitution in consumption (see eq. (2)) and in production (see eqs. (15) and (11)), it is possible to extend the model to allow different prices for firms and households. However this generalization requires additional assumptions that rule out arbitrage.

where d_t^{lj} is nominal profits, $x_{lj,t}^{mi}$ and $h_{lj,t}^{mi}$ are respectively the quantities sold to firm m in sector i as material input and investment good, and the other notation was previously defined. The terms in the right-hand side are, respectively, revenue from sales to households and firms, the wage bill, total expenditure on investment goods, total expenditure on material inputs, the cost of adjusting the capital stock and the cost of changing prices. The firm's problem is to maximize

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{t-\tau} \left(\frac{\Lambda_\tau}{\Lambda_t} \right) \left(\frac{d_t^{lj}}{P_t} \right), \quad (20)$$

by selecting optimal sequences $\{n_t^{lj}, x_{mi,t}^{lj}, h_{mi,t}^{lj}, k_{t+1}^{lj}, p_t^{lj}\}_{t=\tau}^{\infty}$ subject to the production function (9), the law of motion for capital (13), total demand for good j , the condition that supply equals demand, and the initial capital stock and price. The variable Λ_t is the household's marginal utility of wealth at time t . The kernel $\beta^{t-\tau} \Lambda_\tau / \Lambda_t$ is used to value profits because the firm is owned directly by households through the stock market.

In order to solve this problem, we first conjectured the form of the demands $x_{lj,t}^{mi}$ and $h_{lj,t}^{mi}$. Given the functional forms employed here, natural candidates are

$$\begin{aligned} x_{lj,t}^{mi} &= \kappa_{ji} \left(p_t^{lj} / p_t^j \right)^{-\theta} \left(p_t^j / Q_t^{H^i} \right)^{-1} X_t^{mi}, \\ h_{lj,t}^{mi} &= \zeta_{ji} \left(p_t^{lj} / p_t^j \right)^{-\theta} \left(p_t^j / Q_t^{H^i} \right)^{-1} H_t^{mi}. \end{aligned}$$

Then we showed that in equilibrium these are indeed the optimal demands for the good produced by firm l in sector j on the part of other firms. For these demand functions, the relations $\sum_{i=1}^J \int_0^1 p_t^{mi} x_{mi,t}^{lj} dm = \sum_{i=1}^J p_t^i x_{i,t}^{lj} = Q_t^{X^j} X_t^{lj}$ and $\sum_{i=1}^J \int_0^1 p_t^{mi} h_{mi,t}^{lj} dm = \sum_{i=1}^J p_t^i h_{i,t}^{lj} = Q_t^{H^j} H_t^{lj}$ hold.

2.3 The Government

The government comprises both fiscal and monetary authorities. Fiscal policy consists of lump-sum transfers to households each period that are financed by printing additional money. Thus, the government budget constraint is

$$\Upsilon_t / P_t = m_t - m_{t-1} / \pi_t, \quad (21)$$

where the term in the right-hand side is seigniorage revenue at time t . Money is supplied by the government according to $M_t = \mu_t M_{t-1}$, where μ_t is the gross rate of money growth.

2.4 Shocks

The preference shock η_t , the technology shocks z_t^j and rate of money growth μ_t are exogenous and follow the processes

$$\begin{aligned}\ln(\eta_t) &= (1 - \rho_\eta) \ln(\eta_{ss}) + \rho_\eta \ln(\eta_{t-1}) + \epsilon_{\eta,t}, \\ \ln(z_t^j) &= (1 - \rho_{z^j}) \ln(z_{ss}^j) + \rho_{z^j} \ln(z_{t-1}^j) + \epsilon_{z^j,t}, \\ \ln(\mu_t) &= (1 - \rho_\mu) \ln(\mu_{ss}) + \rho_\mu \ln(\mu_{t-1}) + \epsilon_{\mu,t},\end{aligned}$$

where ρ_η , ρ_{z^j} , and ρ_μ are strictly bounded between -1 and 1 , $\ln(\eta_{ss})$, $\ln(z_{ss}^j)$ and $\ln(\mu_{ss})$ are the unconditional means of their respective shocks, and the innovations $\epsilon_{\eta,t}$, $\epsilon_{z^j,t}$ and $\epsilon_{\mu,t}$ are mutually independent and serially uncorrelated, and have zero mean and variances σ_η^2 , $\sigma_{z^j}^2$, and σ_μ^2 , respectively.

2.5 Aggregation

In equilibrium, net private bond holdings equal zero because households are identical, the total share holdings in sector j add up to one, and firms in the same sector are identical, which implies that $p_t^j = p_t^{lj}$, $c_t^j = c_t^{lj}$, $n_t^j = n_t^{lj}$ and $d_t^j = d_t^{lj}$. Thus, the aggregate counterpart of the representative household's budget constraint is

$$\sum_{j=1}^J \frac{p_t^j c_t^j}{P_t} + m_t = \sum_{j=1}^J \frac{w_t^j n_t^j}{P_t} + \sum_{j=1}^J \frac{d_t^j}{P_t} + \frac{m_{t-1}}{\pi_t} + \frac{\Upsilon_t}{P_t}. \quad (22)$$

Substituting the government budget constraint (21) into this equation and multiplying through by the price level yield

$$\sum_{j=1}^J p_t^j c_t^j = \sum_{j=1}^J w_t^j n_t^j + \sum_{j=1}^J d_t^j. \quad (23)$$

Let $V_t^j \equiv p_t^j \left(c_t^j + \sum_{i=1}^J x_{j,t}^i + \sum_{i=1}^J h_{j,t}^i \right)$ denote the value of gross output produced by sector j . Then, aggregate nominal dividends are equal to

$$\sum_{j=1}^J d_t^j = \sum_{j=1}^J V_t^j - \sum_{j=1}^J w_t^j n_t^j - \sum_{j=1}^J Q_t^{X^j} X_t^j - \sum_{j=1}^J Q_t^{H^j} H_t^j - \sum_{j=1}^J A_t^j, \quad (24)$$

where we have used $\sum_{i=1}^J p_t^i x_{i,t}^j = Q_t^{X^j} X_t^j$ and $\sum_{i=1}^J p_t^i h_{i,t}^j = Q_t^{H^j} H_t^j$, and defined $A_t^j = \Gamma_t^j Q_t^{X^j} + \Phi_t^j p_t^j \left(c_t^j + \sum_{i=1}^J x_{j,t}^i + \sum_{i=1}^J h_{j,t}^i \right)$ to be the sum of all adjustment costs in sector j . The nominal

value added in sector j is denoted by Y_t^j , and it is defined as the value of gross output produced by that sector minus the cost of material inputs. That is,

$$Y_t^j = V_t^j - Q_t^{H^j} H_t^j. \quad (25)$$

Substituting (24) and (25) into (23), using $\sum_{j=1}^J p_t^j c_t^j = P_t C_t$, and rearranging yield

$$\sum_{j=1}^J Y_t^j = P_t C_t + \sum_{j=1}^J Q_t^{X^j} X_t^j + \sum_{j=1}^J A_t^j. \quad (26)$$

Then, total output equals household consumption plus investment by all sectors plus the sum of all adjustment costs in all sectors.

Since the equilibrium is symmetric within sectors but asymmetric between sectors, relative sectoral prices are not all equal to one and real wages and allocations are different across sectors. This implies that the state variables of the system include J capital stocks and J real prices. The model is solved numerically by log-linearizing the first-order and equilibrium conditions around the deterministic steady state to obtain a system of linear difference equations with expectations. The rational-expectation solution of this system is found using the method in Blanchard and Kahn (1980).

3 Empirical Analysis

For the empirical part of this project, we concentrate on six broad sectors of the U.S. economy, namely agriculture, mining, construction, durable and nondurable manufacturing, and services. These sector approximately correspond to the Division level of the Standard Industry Classification (SIC). The list of sectors is exhaustive in the sense that their output aggregate to privately-produced U.S. Gross Domestic Product (GDP). The number and size of the sectors was to some extent determined by data availability and computational considerations. SIC sectoral data are available at discrete levels of aggregation (divisions, major groups, industry groups, and industries) and service categories tend to be less finely divided than manufacturing ones. Focusing on these six sectors has four advantages. First, these sectors are natural partitions of the U.S. economy. Second, they are associated with concrete goods, as opposed to the generic distinction between “sticky-price” and “flexible-price” goods in some two-sector models (see, among others, Ohanian, Stockman and Kilian, 1995). Third, they are computationally manageable. The computation of the steady state requires the solution of $3J + 1$ nonlinear equations, that is 19 equations for the six-sector model at division level but 91 equations for the thirty-sector model at the major-group level of the SIC. Finally, there are sufficient sectoral data to identify their sector-specific parameters.

Agriculture includes the production of crops and livestock, agriculture-related services, and forestry. Mining includes oil and gas extraction, metallic and nonmetallic mining, and mining-related services. Construction includes building construction, heavy construction (for example, bridges and roads) and special trade contractors. Although mining and construction respectively represent only 2.5 and 5.2 percent of privately-produced GDP, their contribution to aggregate fluctuations may be large because they produce most of the energy goods and fixed capital that enter the production function of all sectors. The classification of manufacturing between durables and nondurables is based on the definition of good durability by the Bureau of Labor Statistics (BLS). Finally, services include, among others, retail trade, transportation, finance and health.⁴ As in NIPA, rental housing is treated as a service for the purpose of computing households' expenditure shares.

3.1 Estimation Strategy

The estimation of this model is computationally demanding because the number of parameters is large and the steady state and solution of the model need to be calculated in every iteration of the algorithm that optimizes the statistical objective function. The computation of the steady state is particularly costly because it requires solving simultaneously a fairly large system of nonlinear equations. To address this difficulty, we exploit the properties of the model and various data to estimate or calibrate the parameters that determine the steady state, and then (with those parameters values fixed) estimate the parameters that drive the dynamics of the model using the Generalized Method of Moments (GMM).

Under the assumption that the aggregators (10) and (14) are Cobb-Douglas, the input weights ζ_{ij} and κ_{ij} are respectively equal to the share of sector i in the material and investment input expenditures by sector j . These shares are computed using data from the U.S. Input-Output (I-O) accounts. Input-Output accounts show how industries use output from and provide input to each other to produce gross domestic product. The Bureau of Economic Analysis (BEA) prepares both benchmark and annual I-O accounts. Benchmark accounts are produced every five years using detailed data from the economic censuses conducted by the Bureau of the Census. Annual accounts are prepared for selected years between the benchmarks using less comprehensive data than those from the censuses. We use the 1992 benchmark accounts because both the Use Table and the Capital Flow Table are electronically available for that year.⁵ The shares ζ_{ij} are computed using the Use Table,

⁴Durable (nondurable) manufacturing consists of Groups 24, 25 and 32 to 39 (20 to 23 and 26 to 31) in Division D. Services consists of Divisions E to I.

⁵The only other year for which this is true is 1982, but documentation is more extensive and user friendly for 1992 than for 1982. The data are available at www.bea.gov/industry.

which contains the value in producer prices of each input used by each U.S. industry. These shares are reported in Table 1.⁶ Notice that services are a substantial proportion of the material inputs consumed by all sectors. The shares κ_{ij} are computed using the Capital Flow Table (CFT), which shows the purchases of new structures, equipment and software, allocated by using industry in producer prices. These shares are reported in Table 2. Notice that most investment goods are produced by the construction and durable manufacturing sectors. The service sector has nonnegligible weights because it produces goods that are ancillary to investment, for example, engineering and landscaping services. Mining produces most of its own capital stock because exploration, shafts and wells in the oil industry are coded as goods produced in the mining sector in the I-O accounts. By construction, $\zeta_{ij}, \kappa_{ij} \in [0, 1]$ and $\sum_{i=1}^J \zeta_{ij} = \sum_{i=1}^J \kappa_{ij} = 1$ for all j .

Estimates of the production function parameters are constructed using the yearly data on nominal expenditures on capital, labor and material inputs for each sector collected by Dale Jorgenson for the period 1958 to 1996. Observations are available for more than 30 sectors but aggregation up to the division level of the SIC is straightforward.⁷ The nominal expenditures predicted by the model may be obtained from the first-order conditions of the firm's problem:

$$\nu^j \left(\psi_t^j P_t y_t^j \right) = w_t^j n_t^j, \quad (27)$$

$$\gamma^j \left(\psi_t^j P_t y_t^j \right) = \sum_{i=1}^J p_t^i h_{i,t}^j, \quad (28)$$

$$\alpha^j \left(\psi_t^j P_t y_t^j \right) = \left(\left(\frac{\Lambda_{t-1}}{\beta \Lambda_t} \right) \Omega_{t-1}^j - (1 - \delta) \Omega_t^j \right) P_t k_t^j + Q_t^{X^j} k_t^j \left(\frac{\partial \Gamma_t}{\partial k_t^j} \right), \quad (29)$$

where ψ_t^j and Ω_t^j are, respectively, the real marginal cost and the real shadow price of capital in sector j . (Since, in equilibrium, firms in the same sector are identical, the firm

⁶We equate commodities with sectors as in our theoretical model where goods of type j are produced exclusively by sector j . This means that we implicitly treat the Make Table of the I-O accounts as diagonal and it is the reason we construct the weights ζ_{ij} using the Use Table alone. The Make Table contains the value of each commodity produced by each domestic industry and, in reality, it is not perfectly diagonal because there is a small proportion of commodities that are produced by industries in a different SIC division. For example, the I-O accounts treat printed advertisement as a business service (Division I) even though it is produced by the printing and publishing sector (Division D). In order to examine the quantitative importance of the off-diagonal terms, we computed the share of each commodity type that is produced in each sector. Since the diagonal elements vary between 0.988 and 1, the original assumption of the model that associates each commodity type with only one sector seems to be a reasonable approximation for the U.S. economy at this level of disaggregation.

⁷Jorgenson records separately expenditures on material and energy inputs. In order to be consistent with the model, where energy is indistinguishable from other material inputs, we add these two series into a single expenditure category. The complete data set is available at <http://post.economics.harvard.edu/faculty/jorgenson/data>. The data are described in detail in Jorgenson and Stiroh (2000). The values of labor, capital, material and energy inputs are respectively labeled vl , vk , vm , and ve in the data set.

superscripts have been dropped.) The right-hand sides of these equations are, respectively, the wage bill, total expenditures on material inputs, and the opportunity cost (net of capital gains) of the capital stock plus net adjustment costs. Jorgenson’s data are empirical counterparts of these expressions. However, in the case of capital, the mapping is imperfect because the data do not include adjustment costs and take into account distortionary taxes, which our model abstracts from (see Jorgenson and Stiroh, 2000, Appendix B, for additional details).⁸ The data set does not contain observations on $\psi_t^j P_t y_t^j$, but it is possible to construct estimates of α^j , ν^j , and γ^j using two of the following three ratios: (27)/(28), (27)/(29) and (28)/(29), and the condition $\nu^j + \alpha^j + \gamma^j = 1$ to obtain a system of three equations with three unknowns.⁹ The unique solution of this system delivers an observation of the production function parameters for that year. Estimates of ν^j , α^j and γ^j are the sample averages of these yearly observations and their standard deviations are given by $\sqrt{\sigma^2/T}$ where $T = 39$ is the sample size and σ^2 is the variance of the yearly observations.¹⁰ Estimates are reported in Table 3. These estimates indicate that materials are a quantitatively important component in the production functions of all sectors and support our modeling decision to explicitly characterize their productive role. They also indicate substantial heterogeneity in capital, labor and material intensities across sectors. For example, mining is very intensive in capital; construction, agriculture and manufacturing are intensive in materials but not in capital; and services are equally intensive in labor and materials. This heterogeneity is quantitatively important and statistically significant. That is, the difference in parameter estimates across sectors is numerically large and the null hypothesis that α , ν and γ are the same in all sectors is rejected by the data.

The subjective discount rate is estimated by the sample average of the inverse of the gross *ex-post* real interest rate for the period 1959Q2 to 2002Q4. This estimate is $\beta = 0.997$ (0.0005), where the term in parenthesis is the standard error. The depreciation rate is set to $\delta = 0.02$. In previous sticky-price models, the elasticity of substitution between goods

⁸In order to quantify the size of the capital adjustment costs implied by the model, we simulated the artificial economy for 3500 periods using the parameter estimates reported below and found that they vary from 0.001% of output in construction to 0.2% in mining. It is interesting to note that these are respectively the least and the most capital-intensive sectors of the U.S. economy. These magnitudes are in rough agreement with empirical estimates based on sectoral data (see, Groth, 2008 and the discussion below in Section 3.2) and suggest that, as far as it concerns capital adjustment costs, the misspecification implied by using Jorgenson data is probably small.

⁹Given any two ratios, the third one is redundant and may be trivially derived from the other two. Hence, estimates of the production function parameters are independent of the particular pair of ratios employed.

¹⁰Note that in deriving Equation (29) from the first-order condition for k_{t+1}^j , we used the assumption of rational expectations. Hence, this equation holds only up to a forecast error term. This adds extra noise to the yearly estimates of all production function parameters. However, since the variance of this forecasts error is likely to be small compared with that of the other terms, and since we average over yearly estimates, it is reasonable to assume that the effect of this error on point estimates is small.

(θ) is calibrated to values between 6 (for example, Ireland , 2001) and 11 (for example, Barsky, House and Kimball, 2007). We use the intermediate value $\theta = 8$, meaning that the markup over marginal cost is approximately 15 percent, but results appear robust to using values similar to those used in earlier literature. The consumption weights and ς were taken from Horvath (2000). Horvath measures the consumption weights as the average expenditure shares in NIPA from 1959 to 1995. The shares for agriculture, mining, construction, durable manufacturing, nondurable manufacturing and services are, respectively, 0.02, 0.04, 0.01, 0.16, 0.29 and 0.48. (Horvath does not report standard errors for these estimates.) Horvath computes ς from a regression of the change in the relative labor supply on the change in the relative labor share in each sector. Since his results indicate that $\varsigma = 0.9996$ (0.0027), we set $\varsigma = 1$ in our empirical analysis. For the estimation of the model, the unconditional means and autoregressive coefficients of the productivity shocks are assumed to be same in all sectors (that is, $z_{ss}^j = z_{ss}$ and $\rho_{zj} = \rho_z$ for all j) but the standard deviations of the innovations are allowed to vary across sectors.¹¹ Since the total time endowment is normalized to be 1, z_{ss} is just a scaling factor.

The rest of the model parameters are estimated by the Generalized Method of Moments (GMM) using sectoral and aggregate U.S. time series at the quarterly frequency for the period 1964Q1 to 2002Q4.¹² The sectoral data consist of quarterly series of PPI (Producer Price Index) inflation for four sectors and real wages for five sectors. The commodity-based Producer Price Indices collected by the BLS for farm products, durable manufactured goods, and nondurable manufactured goods were used to construct sectoral inflation series for agriculture, durable manufacturing, and nondurable manufacturing, respectively. A measure of sectoral inflation in the mining sector was constructed using the weighted average of PPI inflation of the most important mineral in each of the four major groups in this division. The major groups are metal mining, coal mining, oil and gas extraction and nonmetallic minerals (SIC codes 10 to 14, respectively) and the minerals used were iron, coal, crude oil and sand, respectively. The weights are the 1992 shares of each industry in the sectoral GDP, which are 0.063, 0.137, 0.711, and 0.088, respectively. Given these weights, it is clear that inflation in this sector is driven by inflation in crude oil. Unfortunately, no PPIs are available for construction and services for the complete sample period. Sectoral wages

¹¹We also estimated a version of the model where the autoregressive coefficients were sector specific. Estimates ranged from 0.44 (agriculture) to 0.96 (services) but standard errors were relatively large and the hypothesis that they are all equal could not be rejected at standard significance levels. The economic implications of that version of the model are basically the same as those reported here.

¹²The sample starts in 1964 because data on wages in the service sector are available only after this date. After the first half of 2003, the BLS stopped reporting sectoral data under the SIC codes and switched to the North American Industry Classification System (NAICS). This means that pre- and post-2003 sectoral data might not be fully comparable.

in all sectors (except agriculture) are constructed by dividing the monthly observations of Average Weekly Earning of Production Workers by the CPI and averaging over the three months of each quarter. Data on sectoral wages in agriculture are not available. Note that although the data set on sectoral prices and wages is incomplete, sector specific parameters will be identified by our structural estimation approach because these parameters also affect observable aggregate variables through general-equilibrium interactions. Since the raw data are seasonally unadjusted, we control for seasonal effects by regressing each series on seasonal dummies and purging the seasonal components.

The aggregate data consist of the quarterly series of the rate of inflation, the rate of nominal money growth, the nominal interest rate, *per-capita* real money balances, *per-capita* investment and *per-capita* consumption. With the exceptions noted below, the raw data were taken from the Federal Reserve Economic Database (FRED) available at Federal Reserve Bank of St-Louis (<http://research.stlouisfed.org/fred2>). The inflation rate is the percentage change in the CPI. The rate of nominal money growth is the percentage change in M2. The nominal interest rate is the three-month Treasury Bill rate. Real money balances are computed as the ratio of M2 *per capita* to the CPI. Real investment and consumption are measured, respectively, by Gross Private Domestic Investment and Personal Consumption Expenditures *per capita* divided by the CPI. The raw investment and consumption series were taken from NIPA. This data are available from the BEA Web site (www.bea.gov). Real balances, investment and consumption are computed in *per-capita* terms in order to make these data compatible with the model, where there is no population growth. The population series corresponds to the quarterly average of the mid-month U.S. population estimated by the BEA. Except for the nominal interest rate, all data are seasonally adjusted at the source. Since the variables in the model are expressed in percentage deviations from the steady state, all series were logged and quadratically detrended.

The use of GMM for the estimation of the model is motivated by results in Ruge-Murcia (2007). Using Monte-Carlo analysis to compare various methods currently employed to estimate DSGE models, Ruge-Murcia finds that GMM has several desirable attributes. First, GMM is computationally the fastest method among those studied. Second, GMM is affected less severely by the stochastic singularity of DSGE models than Maximum Likelihood. (This observation applies more generally to moment-based methods.) In particular, estimation requires linearly independent moments by GMM but linearly independent variables by ML. The former is a weaker restriction because it is possible to find independent moments that incorporate information about more variables than those that are linearly independent. Third, GMM is generally more robust to misspecification than Maximum Likelihood. This is important because economic models are stylized by definition and misspecification of an un-

known form is likely. Finally, within the class of moment-based estimators, results show that weak identification is more easily addressed in the context of GMM than under procedures that match VAR parameters or impulse responses.

The moments used to estimate the model are the variances and first-order autocovariances of the series mentioned above, namely the rates of money growth, nominal interest, CPI inflation, and PPI inflation in all sectors (except in construction and services), real wages in all sectors (except agriculture), and *per-capita* consumption, investment and real money balances. These 30 moments are used to identify 18 structural parameters. Additional details about the estimation procedure may be found in Appendix A.

3.2 GMM Estimates

GMM estimates of the multi-sector model parameters are reported in Table 4. Estimates of the price rigidity parameter, ϕ , for agriculture, mining, construction, and durable manufacturing are not statistically different from zero. Since $\phi = 0$ corresponds to the case of flexible prices, this result indicates that price flexibility is a reasonable approximation for primary and durable goods. On the other hand, estimates of ϕ for nondurable manufacturing and services are statistically different from zero, with the latter being quantitatively much larger than the former. Also, the null hypothesis that ϕ is the same in all sectors is strongly rejected by the data. In particular, the p -value of the Wald test used to test this hypothesis is less than 0.0001. These results support two conclusions. First, there is heterogeneity in price rigidity across sectors and this heterogeneity is statistically significant and quantitatively important. Second, previous estimates of price rigidity based on aggregate data alone are primarily driven by price rigidity in services.

Our estimates are in qualitative agreement with micro evidence for the U.S. (see, Bils and Klenow, 2004, and Nakamura and Steinsson, 2007) and various European countries (see, for example, Hoffmann and Kurz-Kim, 2004, for Germany, and Baudry *et al.*, 2004, for France). Using final goods and services that enter the CPI in their respective countries, these researchers report heterogeneous price stickiness and less frequent price adjustments for services than for goods.

Quantitatively, it is not possible to directly compare our estimates with those based on micro data because the quadratic cost model used here characterizes price rigidity in terms of the size, rather than the frequency, of price adjustments. In order to address this difficulty, consider the following approach. Compare the linearized sectoral Phillips curve in our model

$$E_t \hat{\pi}_{t+1}^j = \frac{1}{\beta} \hat{\pi}_t^j - \frac{\theta - 1}{\beta \phi^j} (\hat{\Psi}_t^j - \hat{p}_t^j), \quad (30)$$

with the one that would be obtained in a version of the multi-sector model where firms follow Calvo pricing

$$E_t \hat{\pi}_{t+1}^j = \frac{1}{\beta} \hat{\pi}_t^j - \frac{(1 - \varrho^j)(1 - \varrho^j \beta)}{\beta \varrho^j} (\hat{\Psi}_t^j - \hat{p}_t^j). \quad (31)$$

The term ϱ^j is the probability of not changing prices in sector j and, in both equations, the circumflex denotes deviation from steady state. Notice that equations (30) and (31) are isomorphic and that, for given values of the discount rate (β) and elasticity of substitution (θ), there is a correspondence between the rigidity parameter ϕ^j in the quadratic cost function and the Calvo probability, ϱ^j . In particular, given ϕ^j , the sectoral Calvo probability is the (positive) root that solves

$$\frac{\theta - 1}{\phi^j} = \frac{(1 - \varrho^j)(1 - \varrho^j \beta)}{\varrho^j}.$$

These probabilities and the expected price durations that they imply are reported in Table 5. Recall that, since the signal that firms receive under Calvo pricing is independent across firms and across time, the expected price duration is $1/(1 - \varrho^j)$.

These durations may be compared with duration estimates computed from micro data. Mean price durations based on micro data were estimated by the inverse of the monthly frequencies of price changes for selected good categories reported by Bils and Klenow, and Nakamura and Steinsson for the U.S. economy. These calculations were also performed for two large European economies (namely, Germany and France) using data reported by Hoffmann and Kurz-Kim, and Baudry *et al.* The micro-based durations are reported in the last four columns of Table 5. A graphic comparison between the durations implied by the estimated multi-sector model and those computed from micro data is shown in Figure 1. The continuous line is the 45 degree line. Along this line, macro- and micro-based estimates would match perfectly. Despite the large methodological difference between the two approaches, duration estimates are similar for comparable sectors (although, clearly, less so for services). We conclude that, except for services, price rigidity estimates from the multi-sector model and from micro data are in quantitative agreement.

The comparison between macro- and micro-based duration estimates is subject to at least three caveats. First, estimating durations by inverse of frequencies may understate true durations if there is cross-sectional heterogeneity across outlets (see Baharad and Eden, 2004). Second, micro-based durations may be shorter than one quarter because prices are surveyed at the monthly frequency but, by construction, the durations implied by the multi-sector model cannot be shorter than one period, which is a quarter. Finally, good categories in the micro data do not correspond exactly to the sectors used to estimate the multi-sector model. We used instead the category closest in nature to each sector, when available. For

the U.S., Bills and Klenow’s estimate for agriculture is that for raw goods. Nakamura and Steinsson’s estimates for agriculture, durables and nondurables are those for unprocessed food, transportation equipment and processed food, respectively. For Germany (France), estimates for agriculture, mining, durables and nondurables are those for unprocessed food, energy, industrial goods (durable goods), and processed food, respectively.

Estimates based on our multi-sector model indicate larger price rigidity in services than found in most previous micro studies. In what follows, we propose two possible explanations for this result. First, most micro studies abstract from actual and owner-equivalent residential rents. Rents receive a large weight in price indices because they constitute the largest expenditure item by households. For example, in the CPI, actual and owner-equivalent rents receive weights of about 7 and 22 percent, respectively. Rents are also among the most rigid prices in the economy as a result of long-term contracting, transaction costs, and regulation. For example, Genesove (2003) finds that for 29 percent of apartments in the U.S. during the period 1974 to 1981 there was no change in nominal rent from one year to the next, and Hoffmann and Kurz-Kim (2004) report that apartment rents in Germany remain unchanged for more than four years on average. In this paper, as in NIPA, housing is included in the service sector for the purpose of computing the households’ expenditure shares and rents are included in the measure of CPI inflation used to estimate the model.¹³ It is significant that the study by Hoffmann and Kurz-Kim, which includes actual (that is, non-imputed) apartment rents, delivers a duration estimate for service prices that is quantitatively close to ours and larger than found in other micro studies using U.S. and European data that exclude rents. Furthermore, Hoffmann and Kurz-Kim report (p. 22) that excluding rents from their sample decreases the overall duration of price spells from 21 to 16 months. This suggests that abstracting from rents may bias downwards estimates of aggregate price rigidity based on micro data.

Second, most micro studies abstract from intermediate goods. In this paper, goods may

¹³We used CPI inflation so that our results may be compared with those reported in previous literature. The BLS also constructs a CPI index that excludes shelter, as well as price indices for actual and owner-equivalent rents. However, the latter two series are only available starting from January 1981 and 1983, respectively. The CPI indices with and without shelter are highly correlated (around 0.95), but there is some difference in their persistence. In particular, the first-order autocorrelation of CPI inflation is 0.71, while that of inflation based on the CPI excluding shelter is 0.66. On the other hand, the inflation rates of the rent components of the CPI are smoother and substantially more persistent than CPI inflation. For the subsample starting in 1983Q2 (for which all three series are available), the standard deviation of actual rent, owner-equivalent rent and CPI inflation are 0.013, 0.014 and 0.017 respectively, while their autocorrelations are 0.72, 0.33 and 0.24, respectively. These observations tend to support, at least informally, our conjecture that housing rents contribute in a quantitatively important manner to the large estimate of price rigidity in the service sector. A formal check of this conjecture, however, involves estimating a model that explicitly allows for housing decisions on the part of households, a task that is beyond the scope of this paper but that we intend to undertake in future research.

be intermediate, meaning that they are used in the production of other goods. Carlton (1986) studies U.S. micro data on firm-to-firm transactions of intermediate goods and finds long-term relations between buyer-seller pairs and larger price rigidity than that found by micro studies that use final goods alone. This is important because data from the Input-Output accounts show that services is the largest producer of intermediate goods in the U.S. economy. In particular, services account (on average) for 36 percent of the material-input expenditures by other sectors, and for 74 percent of the expenditures by services itself.

The capital adjustment cost parameter is estimated to be 17.13 (9.27). In order to give meaning to this estimate and to allow its comparison with estimates based on other functional forms, it is useful to compute the elasticity of investment with respect to the price of installed capital. The elasticity implied by our estimate is $1/(\delta\chi) = 2.92$ (1.36). This elasticity is similar to estimates by Groth (2008, p. 322) based on sectoral U.K. data. In particular, Groth reports elasticities of 2.11 for services, 3.31 for all manufacturing, 3.04 for durable manufacturing and 5.84 for nondurable manufacturing. Simulations reported below in Table 5 show that our estimate implies an investment volatility of 11.3, which is very similar to that of 10.4 found in U.S. data.

The autoregressive coefficient of productivity shocks is 0.776 (0.044) and the standard deviation of their innovations vary considerably across sectors. In particular, productivity innovations in agriculture, mining and construction are much more volatile than in the other sectors. Finally, estimates indicate that the preference shock is very persistent but has innovations with low volatility, while the monetary shock is moderately persistent but its innovations are volatile.

3.3 Responses to a Monetary Policy Shock

Consider an experiment where, starting at the deterministic steady state, the economy is subjected to an unexpected and temporary increase in the growth rate of the money supply of 1 percent. Thereafter, money growth returns to its steady state at the rate ρ_μ . Figure 1 plots in Panels A through I the dynamic responses of various aggregate and sectoral variables following this monetary shock.

The shock generates a rise in aggregate demand that causes aggregate output to increase (see Panel A). However, this increase is not evenly spread across sectors. The output increase in services and construction is larger than in durable and nondurable manufacturing. In turn, the output increase in manufacturing is larger than in agriculture and mining (see Panel B).¹⁴ The mechanism by which these responses take place are different. The increase

¹⁴Notice that this result does not imply that overall cyclical variations in services are larger than in other

in output in services and durable manufacturing reflects the usual mechanism whereby the monopolistically competitive producer of a sticky-price good partially accommodates an increase in demand by raising its output. On the other hand, the increase in output in construction and durable manufacturing takes place despite the fact that their prices are flexible and is due to the input-output structure of the economy. Firms in other sectors increase their current output and also their demand for investment goods in order to build up their capital stock and meet future demand. Since the production of investment goods is concentrated in construction and durable manufacturing, the output increase in these two sectors is relatively large. Although prices in agriculture and mining are flexible and these sectors do not produce capital goods, their output increases as a result of the rise in demand for material inputs on the part of other sectors in the economy.

Panels C and D plot the responses of hours worked at the aggregate and sectoral levels, respectively. These responses are primarily the result of increased labor demand on the part of firms, and follow the same pattern as the output responses discussed above. However, there is a quantitatively large difference between the response in services and those in the other sectors, which is due to the fact that services is the most labor intensive sector in the economy.

The responses of aggregate and sectoral real wages are respectively plotted in Panels E and F, and are similar to those of hours worked.¹⁵ The dispersion of sectoral hours and wages are smaller than the dispersion of sectoral outputs at all horizons. For example, the ratios of the standard deviation of sectoral hours and wages to that of sectoral outputs in the quarter when the shock takes place are roughly 0.80. This result is due to the assumption that households have a preference for diversity in sectoral labor supply, which acts as a friction to the reallocation of hours across sectors. To see this, consider, for example, a counterfactual experiment where $\varsigma = 2$, meaning that hours worked across sectors are better substitutes than implied by the empirical work in Horvath (2000). In this case, the ratio of the standard deviation of sectoral hours (wages) to that of sectoral outputs increases (decreases) to 1 (0.5). In the limit, as $\varsigma \rightarrow \infty$, hours worked in each sector become perfect substitutes and wages in all sectors are equalized. In terms of hours, the increase in substitutability of labor supply

sectors. The working paper version of this article (Bouakez, Cardia and Ruge-Murcia, 2005b) reports sectoral output volatilities and shows that service output is the least variable among the sectors studied. This is due in part to the fact that productivity shocks to the service sector have a smaller standard deviation than those to other sectors.

¹⁵Aggregate real wages are measured by the index $w_t/P_t = \left(\sum_{j=1}^J (w_t^j/P_t)^{1+\varsigma} \right)^{1/(1+\varsigma)}$. This index has the property that $\sum_{j=1}^J w_t^j n_t^j = w_t N_t$.

across sectors associated with a larger value of ς means that the sectoral dispersion of hours is increasing in ς . These results reflect some degree of labor mobility across sectors and are consistent with work by Davis and Haltiwanger (2001) who find that monetary policy shocks have reallocative effects in U.S. manufacturing.

A monetary policy shock leads to an increase in aggregate and sectoral consumptions, with the largest increases in the consumption of services and nondurable manufactured goods (see Panels G and H). There is also a substantial change in the composition of household consumption. In order to understand this composition change, consider Panel J which shows that the monetary policy shock induces a change in relative prices. As one would expect, the relative price of services declines because its nominal price is the most rigid while those of other goods rise because their nominal prices are comparatively more flexible. Since it is apparent that the increase in household consumption is the smallest for goods whose relative prices rise the most, it follows that the temporary change in the composition of the consumption bundle reflects primarily intratemporal substitution by households.

Panels K and L plot the response of CPI and sectoral inflation rates to the monetary policy shock. All inflation rates increase after the shock, but the increase is more pronounced in flexible-price goods. In comparison, inflation in services increases by much less but it is the most persistent. Since CPI inflation is the weighted sum of sectoral inflations and the weight of services in the CPI is approximately one-half, the dynamics of aggregate inflation at horizons of a year or less are jointly determined by service and non-service sectors. However, since inflation in non-service sectors return faster to the steady state, the CPI inflation dynamics at horizons beyond a year are mostly determined by service inflation.

Finally, the response of the real interest rate is plotted in Panel I. The drop in the real rate is substantial and persistent. However, it is clear from panels I and K, that the response of the nominal interest rate (not shown) is positive and relatively muted. Hence, as symmetric sticky-price models, the multi-sector model does not produce a liquidity effect. The reason is that the estimated money growth process is moderately persistent. Thus, following a monetary policy shock, expected inflation increases by a magnitude that is slightly larger than the decrease in the real interest rate. It follows that the net effect of the monetary shock on the nominal interest rate is quantitatively small and positive.

The responses in Figure 1 are consistent with evidence from vector autoregressions. Barth and Ramey (2001), Dedola and Lippi (2005) and Peersman and Smets (2005) study the output effects of monetary policy shocks on different manufacturing industries and find positively-correlated output responses across industries and quantitatively large responses on the part of durable good producers. Erceg and Levin (2006) find that household consumption of durable goods and residential structures rises after a cut in the Federal Funds Rate.

Our results also shows that input-output interactions are important for generating realistic dynamics. Two-sector models with a flexible- and a sticky-price sectors but without input-output interactions predict a large change in relative prices following a monetary policy shock (see, among others, Ohanian, Stockman and Kilian, 1995). This relative-price change induces a substitution effect in consumption that generates a counterfactual negative comovement in sectoral outputs and consumptions. In our model, the output effects of a monetary policy shock arise from price rigidity in some sectors of the economy and are transmitted to other sectors via a realistic input-output structure. Although relative prices change and induce intratemporal substitution by households, this effect does not dominate the income effect associated with the increase in money balances. As a result, all sectoral household consumptions rise. This happens because the increased demand on the part of firms moderates the dispersion in relative prices and because goods produced in different sectors are imperfect consumption substitutes. Overall, the input-output structure is important to generate positive output and consumption comovement across sectors and a large response by investment-good producers following a monetary policy shock.

3.4 Comparison with a Symmetric Model

The previous sections document substantial heterogeneity in technology and price rigidity across U.S. sectors and show that this heterogeneity is important to understand the transmission of monetary policy. The symmetric DSGE models developed in earlier literature counterfactually predict that all sectors react identically to monetary policy shocks. VAR evidence on heterogeneous sectoral responses and micro evidence on factor reallocations following monetary policy shocks are evidence against the assumption of symmetry. However, one must keep in mind that symmetric models were primarily designed to understand the behavior of aggregate variables. Therefore, this section constructs and estimates a symmetric version of the multi-sector model, and compares the predictions of both models concerning the unconditional second moments and impulse responses of aggregates.

The symmetric version of our model assumes that production function parameters and price rigidity are the same in all sectors; allows material inputs in production but assumes that sectors buy goods from each other in identical proportions; and permits sectoral productivity shocks but with the same persistence and volatility for all sectors. The parameters of the production functions are estimated using the same procedure described in Section 3.1 but using the sum of input expenditures by all sectors. Then, the estimated output elasticities with respect to capital, labor, and materials are 0.163 (0.002), 0.340 (0.002), and 0.497 (0.003), respectively. The consumption, investment and material input weights (that

is, ξ_j , κ_{ij} and ζ_{ij} , respectively) are all set to $1/6$ and, consequently, the Use and the Capital Flow Tables of this economy are symmetric. The values of the discount factor, the depreciation rate, the elasticity of substitution between same-sector goods, and the parameter that determines the elasticity of substitution between sectoral hours are the same as those used in the multi-sector model. That is, $\beta = 0.997$, $\delta = 0.02$, $\theta = 8$ and $\varsigma = 1$.

The rest of the symmetric model parameters are estimated by GMM using the same data and weighting matrix used to estimate the multi-sector model. Estimates are reported in Table 4. The estimate of the capital adjustment cost parameter (χ) is smaller than that of the multi-sector model but it is nonetheless contained in the 95 percent confidence interval around the latter. The standard deviation of productivity innovations and the price rigidity parameter are statistically different from zero with the former (latter) being larger (smaller) than the weighted average of multi-sector estimates. Estimates of the other parameters are similar in both models.

The standard deviations and autocorrelations predicted by both models and those of U.S. data are reported in Table 7. The moments predicted by the symmetric and multi-sector models are similar, and in general agreement with data. However, the volatility of hours and wages in both models are respectively larger and smaller than in the data (although the quantitative difference is only moderate). Also, the predicted inflation autocorrelation is less than in the data. Earlier literature on sticky-price DSGE models suggests that it is difficult to capture the large serial correlation of the inflation rate unless indexation to lagged inflation is explicitly included into the model.

Finally, consider the impulse responses of aggregate variables following a monetary policy shock. Figure 3 plots the responses of aggregate output, consumption, investment, hours, real wages, and CPI inflation for the multi-sector and symmetric models. Responses are qualitatively similar but there are important quantitative differences. First, the multi-sector model predicts a larger response on the part of household consumption. Second, the multi-sector model predicts generally smaller but more persistent responses in output, investment, hours and CPI inflation. In order to quantify this difference in persistence, we computed mean lags and report them in Panel C of Table 6. The mean lag is a summary measure of the speed with which the variable responds to the shock and is calculated here as the time elapsed between the moment the shock hits and the moment 50 percent of its initial effect has dissipated. From these estimates, it is clear that production heterogeneity amplifies the propagation mechanism of the model and delivers additional persistence in response to monetary disturbances.¹⁶

¹⁶A similar result is found by Carlstrom, Fuerst, Ghironi and Hernandez (2005) using a calibrated two-sector model with heterogeneous price rigidity and labor immobility across sectors.

4 Conclusions

This paper studies the effects of monetary policy through the lens of a multi-sector model. In contrast to previous sticky-price DSGE models that impose symmetry across sectors, this paper explicitly incorporates heterogeneity in production and frictions, which is a prominent feature of the data. Our analysis demonstrates that modeling realistically the input-output structure of the economy is important to understand the transmission of monetary policy. In particular, it shows how the output effects of a monetary policy shock arise from price stickiness in some sectors and are transmitted to others through input-output interactions, and reveals why some sectors (*e.g.*, construction and durable manufacturing) are more sensitive to monetary disturbances than others, even if their prices are flexible.

Econometric results also indicate that price rigidity is statistically different across sectors and that services account for most of the rigidity observed at the aggregate level. This paper shows that a sticky-price DSGE model that permits heterogeneity at the sectoral level can help reconcile the macro and micro literature on price rigidity. The results here agree with the micro literature that most good prices are relatively flexible but show that their output may still react to monetary shocks if they are a material or investment input in the production of other goods whose prices are rigid. The quantitative discrepancy between the price rigidity in services in this paper and in micro-based studies is likely to be due to the fact that the latter usually abstract from rents. This is important because services receive a relatively large weight in the CPI. Then, estimates of aggregate price rigidity based, among other times series, on CPI inflation are mainly driven by price rigidity in services.

Table 1. U.S. Input-Output Matrix 1992
One-Digit Level SIC

Producer	Consumer					
	Agriculture	Mining	Construction	Durables	Nondurable	Services
Agriculture	0.390	0.001	0.011	0.009	0.126	0.007
Mining	0.002	0.334	0.015	0.012	0.092	0.027
Construction	0.020	0.034	0.002	0.010	0.010	0.056
Durables	0.027	0.090	0.458	0.571	0.044	0.061
Nondurables	0.249	0.062	0.096	0.095	0.432	0.112
Services	0.311	0.479	0.419	0.304	0.295	0.738

Notes: This Table reports the share of total material-input expenditures by the consuming sector that goes into goods from the producing sector. (For example, 39 percent of the material-input expenditure by agriculture goes into goods produced by agriculture itself.) The shares were computed by the authors using the table “The Use of Commodities by Industries” for 1992 produced by the BLS. Columns may not add up to one due to rounding.

Table 2. U.S. Capital Flow Table 1992
One-Digit Level SIC

Producer	Consumer					
	Agriculture	Mining	Construction	Durables	Nondurable	Services
Agriculture	0.000	0.000	0.000	0.000	0.000	0.000
Mining	0.000	0.547	0.000	0.000	0.000	0.000
Construction	0.185	0.160	0.012	0.217	0.201	0.533
Durables	0.582	0.244	0.784	0.634	0.645	0.356
Nondurables	0.000	0.001	0.000	0.005	0.006	0.006
Services	0.233	0.047	0.204	0.144	0.148	0.104

Notes: This Table reports the share of total investment expenditures by the consuming sector that goes into goods from the producing sector. (For example, 58 percent of the investment expenditure by agriculture goes into goods produced by durable manufacturing.) The shares were computed by the authors using the 163 × 64 table “Distribution of New Equipment and Structures to Using Industries in Producers’ Prices” for 1992 produced by the BLS. Columns may not add up to one due to rounding.

Table 3. Estimates of Production Function Parameters

Sector	Output Elasticity with Respect to					
	Capital		Labor		Materials	
	Estimate	s.e	Estimate	s.e	Estimate	s.e
Agriculture	0.142*	(0.005)	0.261*	(0.006)	0.597*	(0.006)
Mining	0.380*	(0.009)	0.243*	(0.004)	0.377*	(0.011)
Construction	0.052*	(0.001)	0.394*	(0.004)	0.554*	(0.005)
Durables	0.100*	(0.001)	0.321*	(0.003)	0.579*	(0.002)
Nondurables	0.113*	(0.004)	0.225*	(0.002)	0.662*	(0.006)
Services	0.222*	(0.004)	0.399*	(0.003)	0.379*	(0.007)

Notes: s.e. denotes standard errors. The output elasticities with respect to capital, labor and materials are respectively denoted by α , ν and γ in the text. The superscripts * and † denote the rejection of the hypothesis that the true parameter is zero at the 5 and 10 percent significance levels, respectively.

Table 4. GMM Estimates

Description	Parameter	Multi-Sector		Symmetric	
		Estimate	s.e	Estimate	s.e
Price rigidity in:					
Agriculture	ϕ^1	0.898	1.902	—	—
Mining	ϕ^2	2.077	1.347	—	—
Construction	ϕ^3	4×10^{-5}	1.258	—	—
Durables	ϕ^4	4.244	7.503	—	—
Nondurables	ϕ^5	19.99*	4.792	—	—
Services	ϕ^6	500.23*	16.925	—	—
All sectors	ϕ	—	—	31.32*	7.203
Capital adjustment cost	χ	17.13*	8.019	6.34*	2.261
AR coefficient of productivity shock	ρ_z	0.776*	0.050	0.856*	0.070
SD of productivity innovation in:					
Agriculture	σ_{z1}	0.076*	0.025	—	—
Mining	σ_{z2}	0.340*	0.053	—	—
Construction	σ_{z3}	0.320 [†]	0.185	—	—
Durables	σ_{z4}	3×10^{-5}	26.852	—	—
Nondurables	σ_{z5}	0.109*	0.025	—	—
Services	σ_{z6}	1×10^{-4}	9.115	—	—
All sectors	σ_z	—	—	0.056*	0.027
AR coefficient of preference shock	ρ_η	0.997*	0.024	0.996*	0.072
SD of preference innovation	σ_η	0.002	0.014	0.004	0.036
AR coefficient of monetary shock	ρ_μ	0.395*	0.055	0.369*	0.053
SD of monetary innovation	σ_μ	0.008*	6×10^{-4}	0.008	6×10^{-4}

Notes: See the notes to Table 3.

Table 5. Comparison with Calvo Pricing and Micro Data

Description	Quadratic Costs	Calvo Pricing		Duration Estimated using Micro Data			
		Probability	Expected Duration	U.S.		Germany	France
				B & K	N & S	H & K	Baudry <i>et al.</i>
Price rigidity in:							
Agriculture	0.898	0.103	1.12	0.61	1.31	1.20	1.59
Mining	2.077	0.193	1.24	–	–	0.59	0.47
Construction	4×10^{-5}	5×10^{-6}	1.00	–	–	–	–
Durables	4.244	0.299	1.43	1.12	1.56	2.53	1.81
Nondurables	19.99	0.559	2.27	1.11	3.14	2.87	1.80
Services	500.23	0.890	9.07	1.61	3.79	10.75	4.02

Notes: Duration is measured in quarters. The probability of no price adjustment in the Calvo model is computed given $\beta = 0.997$ and $\theta = 8$. Durations at the micro level were computed by the authors using the mean frequency of price changes for selected good categories reported by Bils and Klenow (2004, Table 2, p. 956), Nakamura and Steinsson (2007, Table 2), Hoffmann and Kurz-Kim (2004, Table 5, p. 19), and Baudry *et al.* (2004, Table 7, p. 43). Their categories do not match exactly to the sectors used to estimate the multi-sector model, so we use instead the category closest in nature to each sector, when available. Except for Germany, services excludes rents, and in the case of Nakamura and Steinsson, excludes travel as well.

Table 6. Aggregate Volatility and Serial Correlation

Variables	U.S.	Model	
	Data	Multi-Sector	Symmetric
<i>A. Standard Deviation</i>			
Output	3.20	4.52	4.74
Consumption	3.09	3.58	3.58
Investment	10.42	11.28	10.46
Hours	2.66	3.91	4.01
Wages	4.15	3.51	3.07
Inflation	3.18	3.17	3.15
<i>B. Autocorrelations</i>			
Output	0.938	0.882	0.903
Consumption	0.947	0.950	0.969
Investment	0.910	0.769	0.814
Hours	0.877	0.833	0.759
Wages	0.953	0.867	0.793
Inflation	0.705	0.355	0.502
<i>C. Mean Lag</i>			
Output	—	4.50	2.60
Consumption	—	4.60	3.64
Investment	—	4.34	1.81
Hours	—	4.32	1.87
Wages	—	4.49	2.82
Inflation	—	3.33	2.17

Notes: The sample used to compute the statistics for U.S. data is 1964:1 to 2002:4. The moments of aggregate consumption, investment and inflation were used in the estimation of both DSGE models.

A GMM Estimation

Define \mathbf{g}_t to be the $q \times 1$ vector of empirical observations on variables whose moments are of interest. For example, in this application, elements of g_t include $\hat{\pi}_t^2$ and $\hat{\pi}_t \hat{\pi}_{t-1}$, where $\hat{\pi}_t$ is the CPI inflation deviation from its trend. The other elements of g_t are the analogous variables for the rates of money growth, nominal interest, and PPI inflation in all sectors (except in construction and services), real wages in all sectors (except agriculture), and per-capita consumption, investment and real money balances. Then, $(1/T) \sum_{t=1}^T \mathbf{g}_t$ are the variances and first-order autocovariances of these U.S. series, with T the sample size. Denote by $E(\mathbf{g}(\varphi))$ the $q \times 1$ vector with the unconditional moments predicted by the model given the parameter values φ . The GMM estimator, φ_{gmm} , is the value of φ that minimizes the loss function

$$\mathbf{G}(\varphi)' \mathbf{W} \mathbf{G}(\varphi), \quad (32)$$

where

$$\mathbf{G}(\varphi) = (1/T) \sum_{t=1}^T \mathbf{g}_t - E(\mathbf{g}(\varphi)),$$

and \mathbf{W} is a $q \times q$ weighting matrix. Under the regularity conditions in Hansen (1982),

$$\sqrt{T}(\varphi_{gmm} - \varphi) \rightarrow N(\mathbf{0}, (\mathbf{D}' \mathbf{W}^{-1} \mathbf{D})^{-1} \mathbf{D}' \mathbf{W}^{-1} \mathbf{S} \mathbf{W}^{-1} \mathbf{D} (\mathbf{D}' \mathbf{W}^{-1} \mathbf{D})^{-1}), \quad (33)$$

where

$$\mathbf{S} = \lim_{T \rightarrow \infty} \text{Var} \left((1/\sqrt{T}) \sum_{t=1}^T \mathbf{g}_t \right), \quad (34)$$

and $\mathbf{D} = E(\partial \mathbf{g}_i(\varphi) / \partial \varphi)$ are assumed to be finite and of full rank. In this application, the weighting matrix \mathbf{W} is the inverse of the matrix with the long-run variance of the moments along the main diagonal and zeros in the off-diagonal elements. The matrix \mathbf{S} is computed using the Newey-West estimator with a Barlett kernel and bandwidth given by the integer of $4(T/100)^{2/9}$. The derivatives $\partial \mathbf{g}_i(\varphi) / \partial \varphi$ that enter the matrix \mathbf{D} are computed numerically at the optimum.

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Fig. 1: Comparison of Macro and Micro Estimates of Price Rigidity

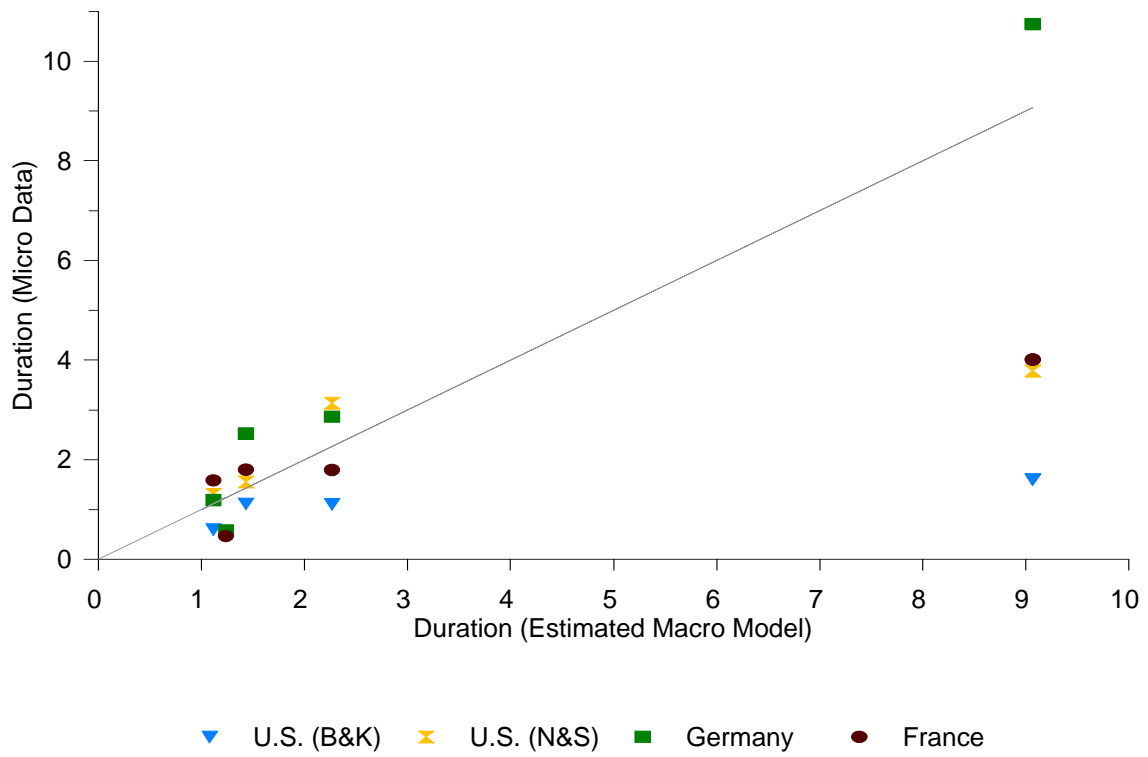
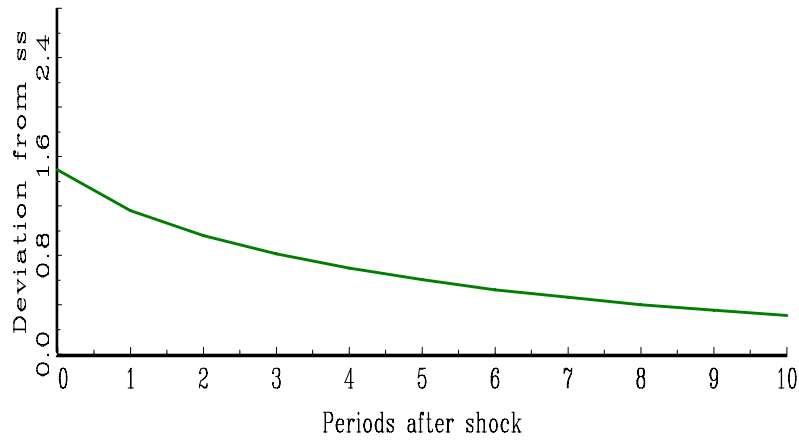
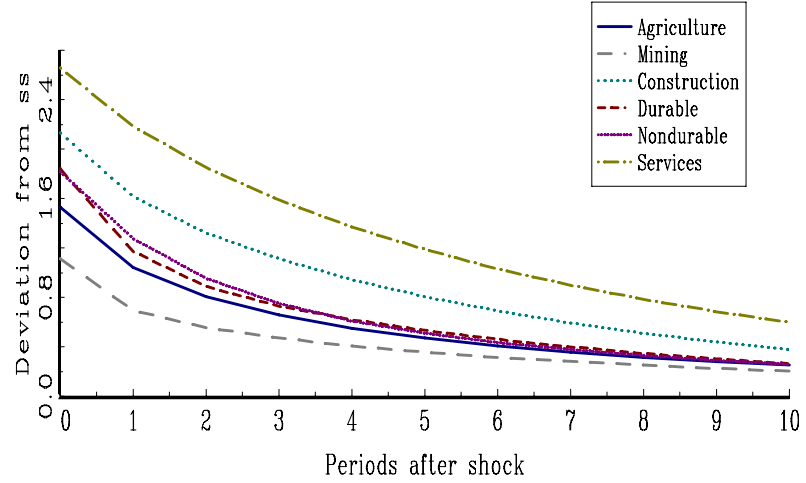


Fig. 2: Response to a Monetary Policy Shock

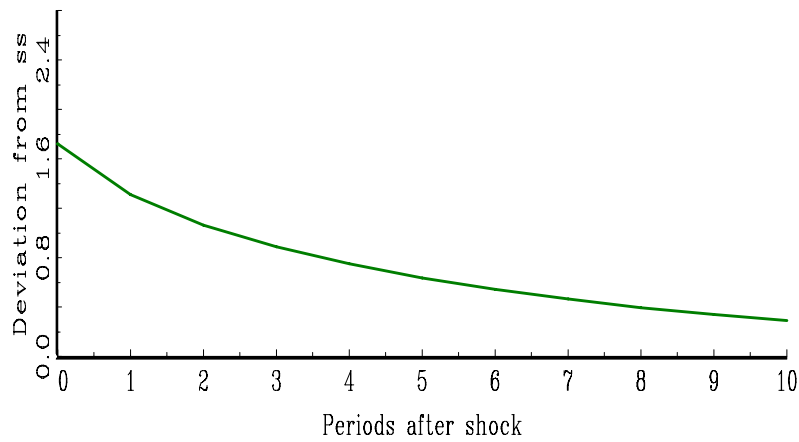
A. Aggregate Output



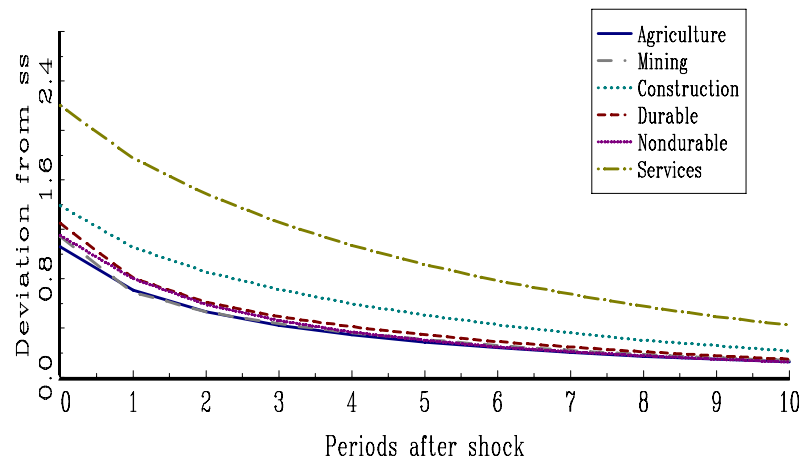
B. Sectoral Output



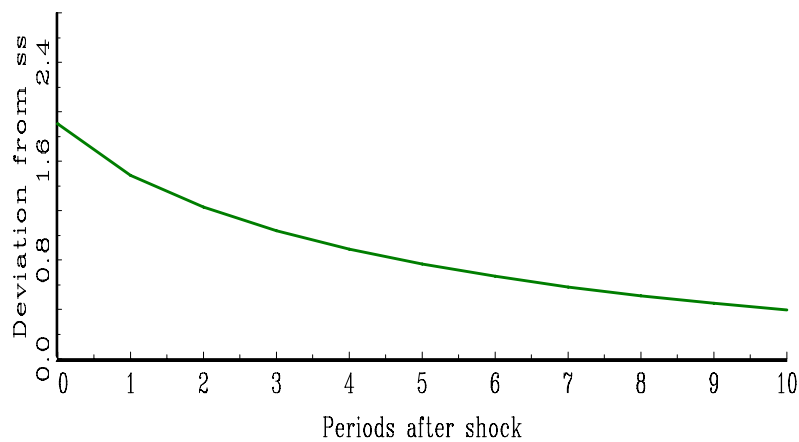
C. Aggregate Hours



D. Sectoral Hours



E. Aggregate Wage



F. Sectoral Wages

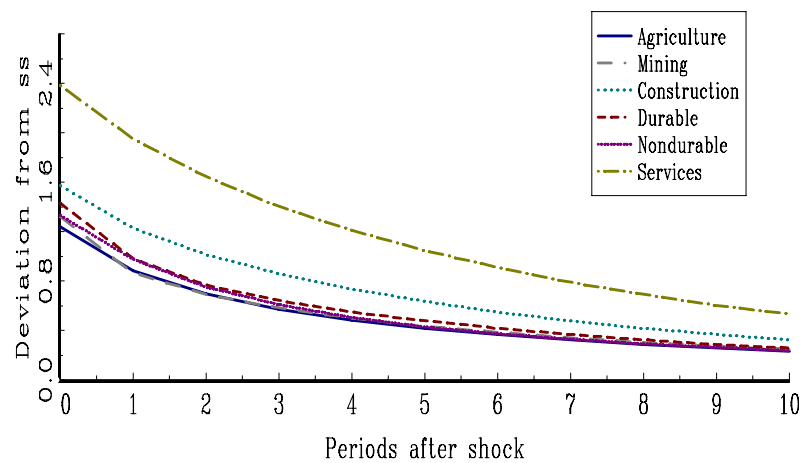
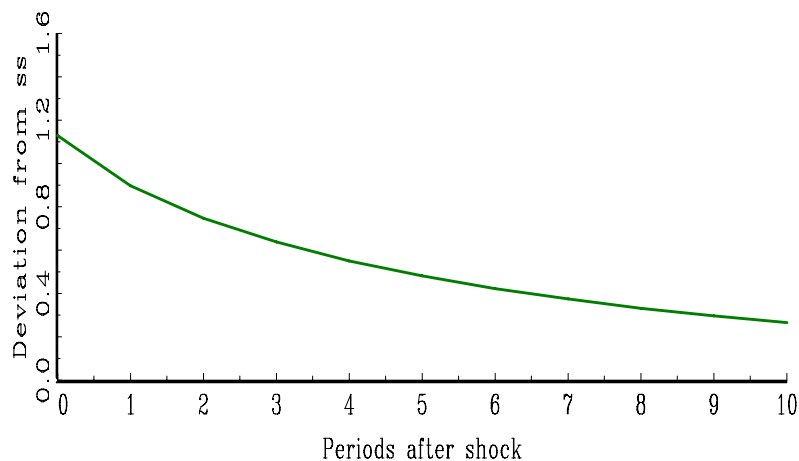
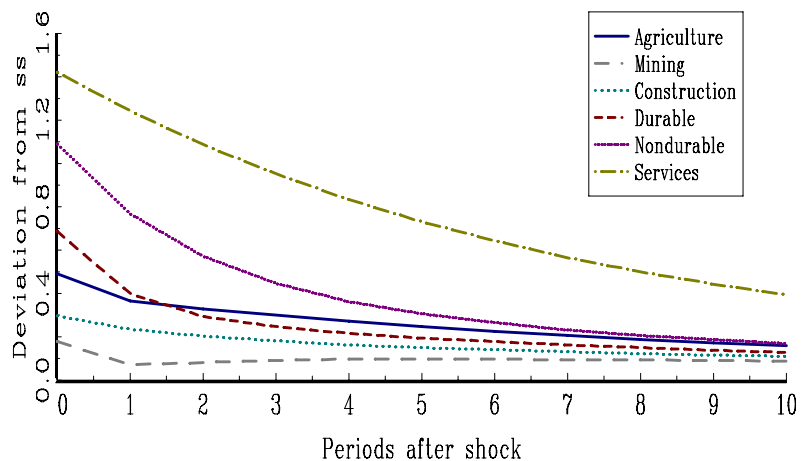


Fig. 2: Response to a Monetary Policy Shock

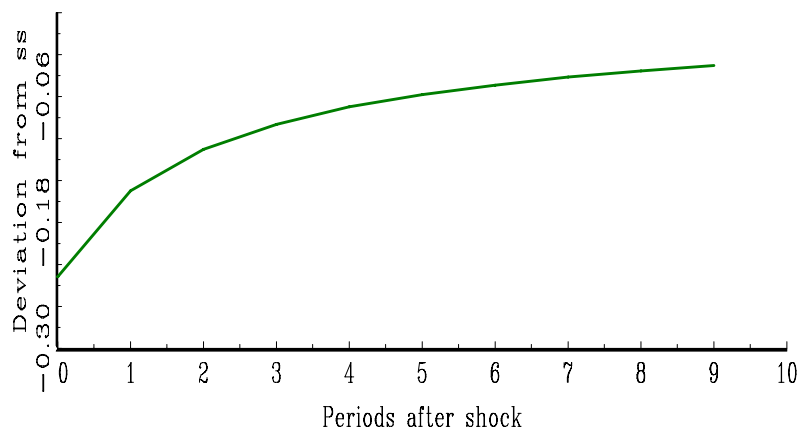
G. Aggregate Consumption



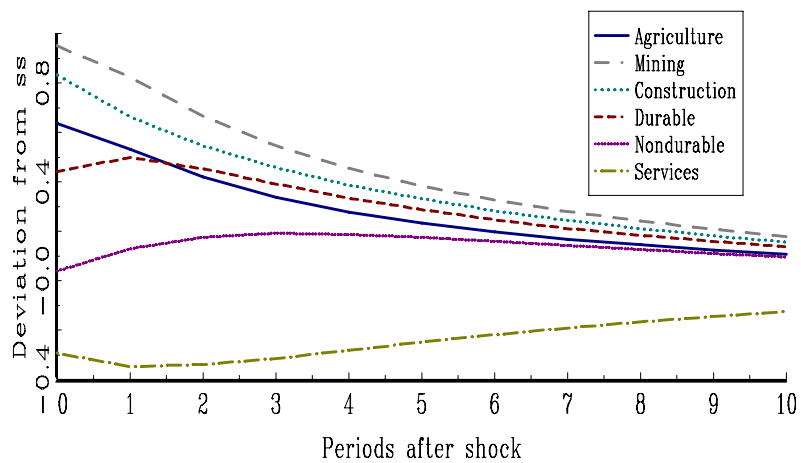
H. Sectoral Household Consumption



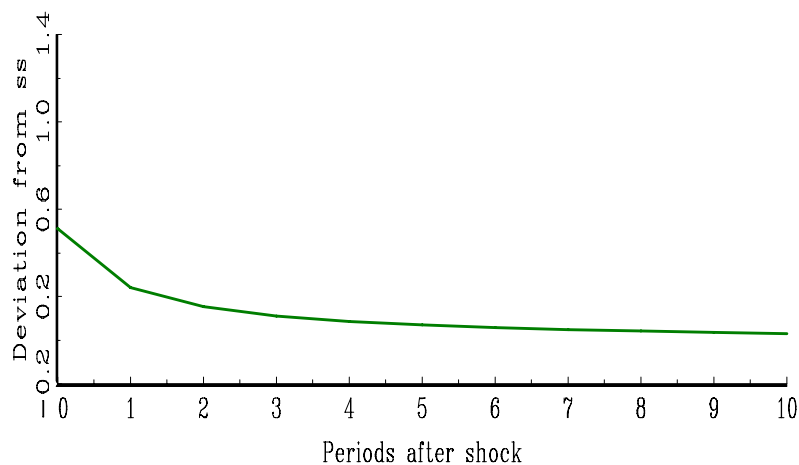
I. Real Interest Rate



J. Relative Prices



K. CPI Inflation



L. Sectoral Inflation

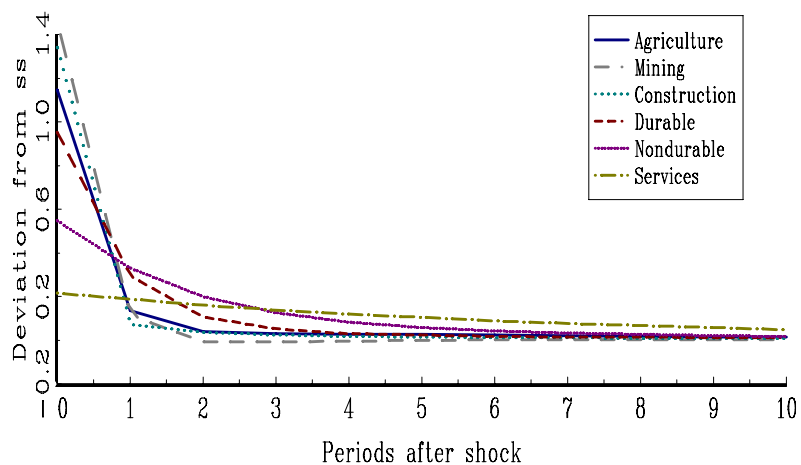
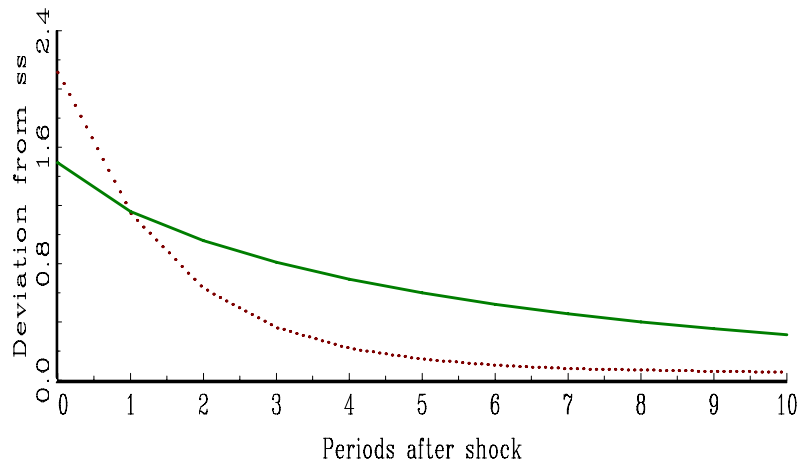
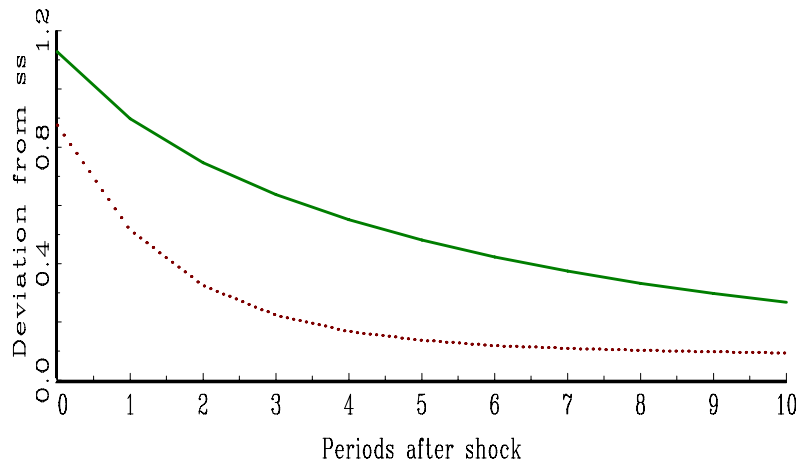


Fig. 3: Comparison with Symmetric Model

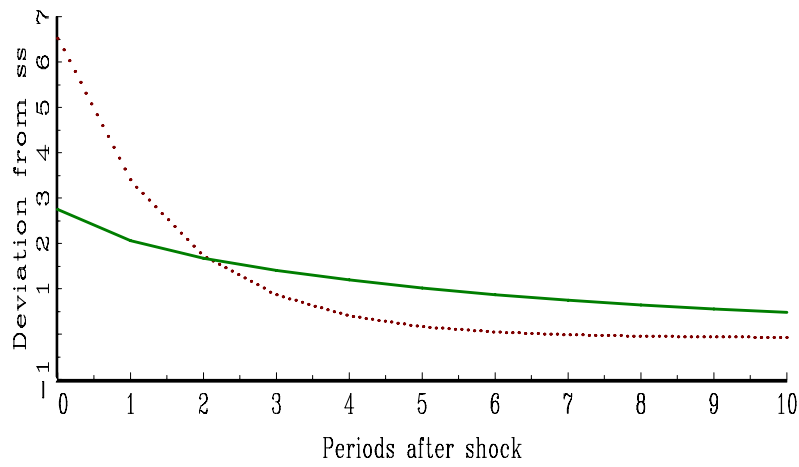
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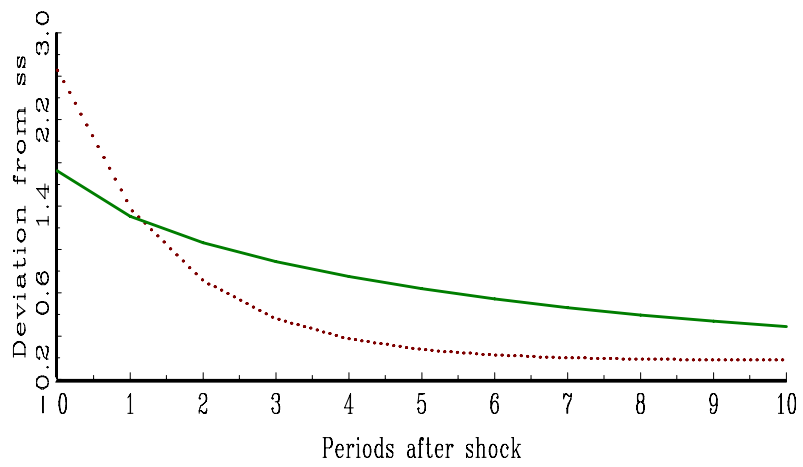
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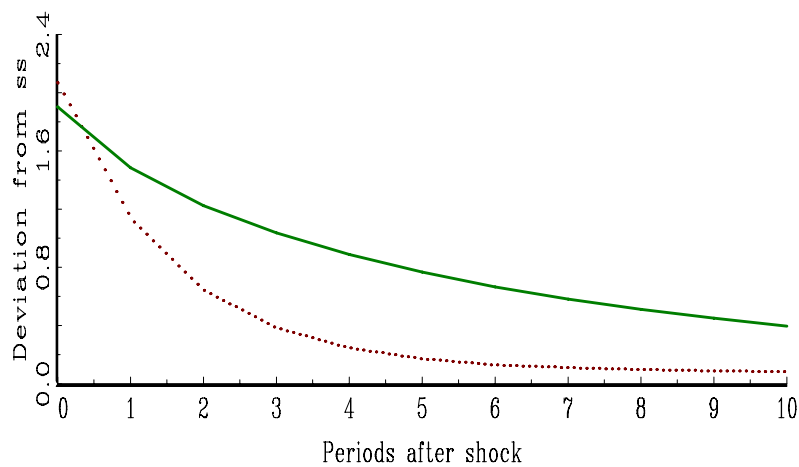
C. Aggregate Investment



D. Aggregate Hours



E. Aggregate Wage



F. CPI Inflation

