The Transmission of Monetary Policy in a Multisector Economy*

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Preliminary and Incomplete

Abstract

This paper constructs and estimates a sticky-price, Dynamic Stochastic General Equilibrium model where production is carried out by heterogenous sectors. Sectors differ in price stickiness, production technology, capital adjustment costs, and the combination of goods used as material and investment inputs. This specification relaxes the usual assumption of symmetry in models of imperfect competition whereby *i*) differentiated goods are produced using exactly the same production function, and *ii*) all goods enter symmetrically into the production of other goods. In this model, sectors use output from other sectors as material and investment inputs following an input-output matrix and capital flow table that represent that of the U.S. economy. By relaxing the assumption of symmetry, this model allows different inflation and output dynamics across sectors in response to monetary policy shocks. The model is estimated by the Simulated Method of Moments (SMM). Econometric results indicate substantial heterogeneity in price stickiness across sectors, and a strong sensitivity to monetary policy shocks on the part of construction and durable manufacturing.

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1 Introduction

This paper constructs and estimates a sticky-price, Dynamic Stochastic General Equilibrium (DSGE) model where production is carried out by heterogenous sectors. By relaxing the usual assumption of symmetry in models of imperfect competition, the model permits different dynamics across sectors in response to monetary policy shocks. Hence, this project formalizes analytically, and evaluates empirically, the notion that different sectors in the economy react differently to changes in monetary policy. In addition, it assesses whether a more realist output structure, that allows heterogeneity and sectoral interactions, modifies earlier conclusions regarding the aggregate effects of monetary policy shocks.

Productive sectors are heterogenous as follows. First, sectors have production functions with different capital, labor, and materials intensities, and use different good combinations as material and investment inputs. In particular, sectors use output from each other following an input-output matrix and capital flow table that represent that of the U.S. economy at the one-digit, Standard Industry Classification (SIC) level. Since each sector uses a different combination of investment goods to build up its capital stock, capital is sector-specific in this model. Second, sectors face different costs to adjust their prices and capital stocks. As a result, there is substantial variation in the frequency and magnitude of price adjustments across goods (see, Bils and Klenow, 2004). Third, sectors are subject to idiosyncratic productivity shocks. The process of the productivity shocks is general enough to allow productivity spillovers and the contemporaneous correlation of productivity innovations across sectors.

In related work, Barth and Ramey (2001) use Vector Autoregressions to examine the effect of monetary policy shocks on different manufacturing industries and report substantial variation in their responses. In particular, durable manufacturing reacts more strongly than nondurable manufacturing to nominal interest rate shocks.

2 A Monetary Economy with Heterogenous Production Sectors

2.1 Households

The economy is populated by identical, infinitely-lived households. The population size is constant and normalized to be one. The representative household maximizes

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{(t-\tau)} U\left(C_t, m_t, 1 - N_t\right), \tag{1}$$

where $\beta \in (0,1)$ is the subjective discount factor; $U(\cdot)$ is an instantaneous utility function that satisfies the Inada conditions and it is assumed to be strictly increasing in all arguments, strictly concave, and twice continuously differentiable; C_t is consumption; $m_t = M_t/P_t$ is real money balances; M_t is the nominal money stock; P_t is an aggregate price index; and N_t is hours worked. Since the total time endowment is normalized to be one, $1 - N_t$ represents leisure time.

Consumption is a CES (Constant Elasticity of Substitution) aggregate over the J available goods:

$$C_t = \left(\sum_{j=1}^{J} \xi^j (c_t^j)^{(\psi-1)/\psi} \right)^{\psi/(\psi-1)}, \tag{2}$$

where $\xi^j \in [0,1]$ are aggregation weights that satisfy $\sum_{j=1}^{J} \xi^j = 1$, c_t^j is the household's consumption of good j, and $\psi > 1$ is the elasticity of substitution between different goods. Notice that since ξ^j can be equal to zero for a given good j, not all goods are necessarily final in the sense that they are ultimately consumed by households. Instead some goods might be intermediate, meaning that they are used only in the production of other goods. Goods are perishable, but we will see below that there exists an investment technology that allows firms to preserve goods in the form of capital. The price index P_t is defined as

$$P_t = \left(\sum_{j=1}^{J} (\xi^j)^{\psi} (p_t^j)^{1-\psi} \right)^{1/(1-\psi)}, \tag{3}$$

where p_t^j is the price of good 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.

As in Horvath (2000), households have a preference for diversity in their labor supply. That is,

$$N_t = \left(\sum_{j=1}^{J} (n_t^j)^{(\varsigma+1)/\varsigma} \right)^{\varsigma/(\varsigma+1)}, \tag{4}$$

where $\varsigma > 0$ and n_t^j is the number of hours worked in sector j at time t. This implies that households are willing to work a positive number of hours in every sector even if wages are not equal in all sectors. This assumption permits heterogeneity in wages and hours worked across sector while preserving the representative agent setup.[1]

[1] The aggregator (4) implies that, strictly speaking, N_t is an index of hours worked. Only in the special case where $\varsigma \to \infty$ and the aggregator is linear does N_t correspond to total hours worked. However, in this case, hours worked in each sector are perfect substitutes and, consequently, the model would predict counterfactually that wages are the same in all sectors.

In what follows, we specialize the instantaneous utility function to

$$U\left(C_t, m_t, 1-N_t\right) = \log(C_t) + \eta_t \log(m_t) + \varrho \log(1-N_t),$$

where $\varrho > 0$ is the utility weight of leisure and η_t is a strictly positive preference shock. The functional form of the instantaneous utility is motivated by theoretical results in Ngai and Pissarides (2004) who show that necessary and sufficient conditions for the existence of an aggregate balanced growth path in a multisector economy are logarithmic preferences and a non-unit price elasticity (that is, $\psi \neq 1$).[2]

There are $J+2$ financial assets in this economy: money, a one-period interest-bearing nominal bond, and shares in 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 sectors $j = 1, \ldots, J$, and then receives interests and dividends, wages from its work in each sector, and a lump-sum transfer from the government. These resources are used to finance consumption and the acquisition of financial assets to be carried out to next period. Expressed in real terms, the household's budget constraint in every period is

$$b_t + \sum_{j=1}^{J} \frac{p_t^j c_t^j}{P_t} + \sum_{j=1}^{J} \frac{a_t^j s_t^j}{P_t} + m_t = \frac{R_{t-1} b_{t-1}}{\pi_t} + \sum_{j=1}^{J} \frac{w_t^j n_t^j}{P_t} + \sum_{j=1}^{J} \frac{(d_t^j + a_t^j) s_{t-1}^j}{P_t} + \frac{m_{t-1}}{\pi_t} + \frac{\Upsilon_t}{P_t}, \quad (5)$$

where $b_t = B_t/P_t$ is the real value of nominal bond holdings, a_t^j is the unit price of a share in sector j, d_t^j is the dividend paid by a share 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, w_t^j is the nominal wage in sector j, and Υ_t is the government lump-sum transfer.

The household's utility maximization is carried out by choosing optimal sequences $\{c_t^j$, n_t^j, M_t, B_t, $s_t^j\}_{t=\tau}^{\infty}$ subject to the sequence of budget constraints (5), no-Ponzi-game conditions, and initial asset holdings $s_{\tau-1}^j$, $M_{\tau-1}$, and $B_{\tau-1}$. The $3J+2$ first-order conditions for this problem determine the consumption demand for each good, money demand, and labor supplied to each sector, and price the nominal bond and the shares in each sector. In particular, the consumption demand for each good is

$$c_t^j = (\xi^j)^{\psi} \left(\frac{p_t^j}{P_t}\right)^{-\psi} C_t, \quad (6)$$

where the price elasticity of demand is $-\psi$. Using this demand function and the definition of the price index, it is easy to show that $\sum_{j=1}^{J} p_t^j c_t^j = P_t C_t$.

[2]The empirical section of this paper reports the result of a Lagrange Multiplier test of the null hypothesis of logarithmic preferences. As we will see below, this hypothesis cannot be rejected at the 5 per cent significance level.

2.2 Production

The production of the J differentiated goods is carried out in monopolistically competitive sectors. The number of firms in each sector is normalized to be one. The representative firm in sector j uses the constant-returns-to-scale technology,

$$y_t^j = (k_t^j)^{\alpha^j} (z_t n_t^j)^{\nu^j} (H_t^j)^{\gamma^j}, \tag{7}$$

where y_t^j is output, z_t is an aggregate labor-augmenting productivity shock, k_t^j is capital, H_t^j is material inputs, and the parameters $\alpha^j, \nu^j, \gamma^j \in (0,1)$ and satisfy the linear restriction $\alpha^j + \nu^j + \gamma^j = 1$. Note that the effect of the productivity shock will be different across sectors because sectors differ in labor intensity.[3]

Material inputs are goods produced by other sectors that are used as inputs in the production of good j. These inputs are combined according to

$$H_t^j = \left(\sum_{i=1}^{J} \zeta_{ij} (h_{i,t}^j)^{(\psi-1)/\psi} \right)^{\psi/(\psi-1)}, \tag{8}$$

where $h_{i,t}^j$ is the quantity of input i purchased by sector j and $\zeta_{ij} \in [0,1]$ is the weight that input i receives in sector j. The weights ζ_{ij} satisfy the condition $\sum_{i=1}^{J} \zeta_{ij} = 1$. Note that the weights ζ_{ij} and quantities $h_{i,t}^j$ are indexed by j because every sector uses a different input combination in its production process.

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

$$k_{t+1}^j = (1-\delta^j) k_t^j + X_t^j, \tag{9}$$

where δ^j is the sector-specific rate of depreciation and X_t^j is an investment technology that aggregates different goods into additional units of capital. Specifically,

$$X_t^j = \left(\sum_{i=1}^{J} \kappa_{ij} (x_{i,t}^j)^{(\psi-1)/\psi} \right)^{\psi/(\psi-1)}, \tag{10}$$

where $x_{i,t}^j$ is the quantity of good i purchased by sector j for investment purposes and $\kappa_{ij} \in [0,1]$ is the weight that good i receives in the production of capital in sector j. The weights κ_{ij} satisfy the condition $\sum_{i=1}^{J} \kappa_{ij} = 1$. The formulation (10) allows each sector to use

[3]In preliminary work, we modeled the productivity shocks as sector-specific. However, it is well known that the effect of uncorrelated sector-specific shocks tends to dissipate through aggregation due to the law of large numbers. We also found that the parameters of the sector-specific shocks were very poorly identified unless *ad hoc* restrictions were imposed during the estimation procedure (for example, that the variance of the innovations of the productivity shocks were the same in all sectors)

different goods in different quantities to accumulate a stock of capital that is sector specific. Adjusting the capital stock, beyond that required to replace the depreciated capital, is assumed to involve a quadratic cost that is proportional to the current capital stock,

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

where χ^j is a nonnegative parameter.

The price of the composite goods H_t^j and X_t^j is given by the indices

$$Q_t^{H^j} = \left(\sum_{i=1}^{J} (\zeta_{ij})^{\psi} (p_t^i)^{1-\psi}\right)^{1/(1-\psi)}, \tag{11}$$

$$Q_t^{X^j} = \left(\sum_{i=1}^{J} (\kappa_{ij})^{\psi} (p_t^i)^{1-\psi}\right)^{1/(1-\psi)}. \tag{12}$$

These price indices are akin to Producer Price Indices (PPI) because they measure prices from the perspective of the seller, as opposed to the CPI that is designed to measure prices from the perspective of the purchaser.

The assumption that the elasticity of substitution between goods is the same in equations (2), (8) and (10) implies that the price elasticity of demand does not depend on the use given to good i by the buyer. Hence, the monopolistic-competitive producer of good i will charge the same price to firms in all sectors and to households regardless of whether i is employed as investment good, consumption good, or material input.[4] Prices are assumed to be sticky. Price stickiness takes the form of a quadratic adjustment cost

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

where $\phi^j \geq 0$ and π_{ss} is the steady-state rate of inflation.

Note that this model allows production sectors to be heterogenous in several dimensions, namely in *i*) capital, labor, and material input intensities, *ii*) depreciation rates, *iii*) adjustment costs to the capital stock, *iv*) price rigidity, and *v*) the combination of goods used as investment and material inputs. The first four points follow from the assumption that the parameters $\alpha^j, \nu^j, \gamma^j, \delta^j, \chi^j$, and ϕ^j are sector specific. The fifth point follows from the observation that the weights κ_{ij} and ζ_{ij} and the quantities $x_{i,t}^j$ and $h_{i,t}^j$ vary across sectors.

[4]It is easy to extend the model to allow different prices for firms and households, but this generalization requires the assumption of frictions that rule out arbitrage. We considered this strategy in the previous version of this paper, but for reasons to be made clear in the empirical section of the paper, it is difficult to identify separately the price elasticities of demand of firms and households.

Since the investment technology is different in each sector, the composition of the capital stock in each sector will be different as well.

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

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

where d_t^j is nominal profits and 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

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{(t-\tau)} \left(\frac{\Lambda_\tau}{\Lambda_t} \right) \left(\frac{d_t^j}{P_t} \right), \tag{13}$$

by selecting optimal sequences $\{n_t^j, x_{it}^j, h_{it}^j, k_{t+1}^j, p_t^j, p_t^j\}_{t=\tau}^{\infty}$ subject to the production function (7), the law of motion for capital (9), total demand for good j, $y_t^j = c_t^j + \sum_{i=1}^{J} x_{j,t}^i + \sum_{i=1}^{J} h_{j,t}^i$, the condition that demand equals supply, and the initial capital stock and prices.

In order to solve this problem, we first conjectured the form of the demands $x_{j,t}^i$ and $h_{j,t}^i$. Given the functional forms employed here, natural candidates are $x_{j,t}^i = (\kappa_{ji})^\psi \left(p_t^j / Q_t^{X^i} \right)^{-\psi} X_t^i$ and $h_{j,t}^i = (\zeta_{ji})^\psi \left(p_t^j / Q_t^{H^i} \right)^{-\psi} H_t^i$. Then we showed that in equilibrium these are indeed the optimal demands of good j on the part of firms in remaining sectors. Note that for these demand functions, the relations $\sum_{i=1}^{J} p_t^i x_{i,t}^j = Q_t^{X^j} X_t^j$ and $\sum_{i=1}^{J} p_t^i h_{i,t}^j = Q_t^{H^j} H_t^j$ hold.

2.3 The Government

The government comprises both fiscal and monetary authorities. There is no government spending or investment. Fiscal policy consists of lump-sum transfers to households each period that are financed by printing additional money in each period. Thus, the government budget constraint is:

$$\Upsilon_t / P_t = m_t - m_{t-1}/\pi_t, \tag{14}$$

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 stochastic gross rate of money growth.[5] In real terms, this process implies

$$m_t \pi_t = \mu_t m_{t-1}. \tag{15}$$

2.4 Shocks

The exogenous shocks to the model, namely the preference shock η_t, the technology shock z_t, and the money supply shock μ_t, follow the joint process

$$\begin{bmatrix} \ln(\eta_t) \\ \ln(z_t) \\ \ln(\mu_t) \end{bmatrix} = \begin{bmatrix} (1-\rho_\eta)^{-1}\ln(\eta_{ss}) \\ (1-\rho_z)^{-1}\ln(z_{ss}) \\ (1-\rho_\mu)^{-1}\ln(\mu_{ss}) \end{bmatrix} + \begin{bmatrix} \rho_\eta & 0 & 0 \\ 0 & \rho_\mu & 0 \\ 0 & 0 & \rho_z \end{bmatrix} \begin{bmatrix} \ln(\eta_{t-1}) \\ \ln(z_{t-1}) \\ \ln(\mu_{t-1}) \end{bmatrix} + \begin{bmatrix} \epsilon_{\eta,t} \\ \epsilon_{\mu,t} \\ \epsilon_{z,t} \end{bmatrix},$$

where ρ_η, ρ_z, and ρ_μ are strictly bounded between -1 and 1; $\ln(\eta_{ss})$, $\ln(z_{ss})$, and $\ln(\mu_{ss})$ are the unconditional means of their respective shocks; and the innovations $\epsilon_{\eta,t}$, $\epsilon_{z,t}$, and $\epsilon_{\mu,t}$ are serially uncorrelated with mean zero and variance-covariance matrix

$$\begin{bmatrix} \sigma_\eta^2 & 0 & 0 \\ 0 & \sigma_z^2 & 0 \\ 0 & 0 & \sigma_\mu^2 \end{bmatrix}.$$

2.5 Aggregation

In equilibrium, *i*) private bond holdings equal zero because households are identical, and *ii*) the total share holdings in sector j must add up to one. Thus, the aggregate counterpart of the representative household's budget constraint (5) is

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

Substituting the government budget constraint (14) into this equation and multiplying through by the price level deliver

$$\sum_{j=1}^{J} p_t^j c_t^j = \sum_{j=1}^{J} w_t^j n_t^j + \sum_{j=1}^{J} d_t^j. \tag{16}$$

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

$$\sum_{j=1}^{J} d_t^j = \sum_{j=1}^{J} V_t^j - \sum_{j=1}^{J} w_t^j n_t^j - \sum_{j=1}^{J} Q_t^{X^j} X_t^j - \sum_{j=1}^{J} Q_t^{H^j} H_t^j - \sum_{j=1}^{J} A_t^j, \tag{17}$$

[5] In preliminary work, we considered the case where monetary policy takes the form of a Taylor-type rule for the nominal interest rate. Calibration results were very similar to the ones reported below for the case where money growth is follows an AR process. These results are available from the corresponding author upon request. See the discussion in Section 3 [to be written].

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,

$$Y_t^j = V_t^j - Q_t^{H^j} H_t^j. \tag{18}$$

Using (18) into (17), substituting the resulting expression into (16), using $\sum_{j=1}^{J} p_t^j c_t^j = P_t C_t$, and rearranging yield

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

Thus, total output equals household consumption plus investment by all sectors plus the sum of all adjustment costs in all sectors. A measure of real output in this economy is

$$\sum_{j=1}^{J} \frac{Y_t^j}{P_t} = C_t + \sum_{j=1}^{J} \frac{Q_t^{X^j} X_t^j}{P_t} + \sum_{j=1}^{J} \frac{A_t^j}{P_t}. \tag{19}$$

The model was solved numerically by log-linearizing the first-order and equilibrium conditions around the deterministic steady state to obtain a system of linear difference equations. Then, the rational-expectations solution of this system was found using the strategy proposed by Blanchard and Kahn (1980). Note that due to the assumed heterogeneity in production, the equilibrium of the model is not symmetric. That is, real prices (including the price of labor) and allocations are different across sectors. Thus, when solving the model, the steady-state allocations of labor, and material and investment inputs need to be computed as the solution of a system of $2J^2 + J$ nonlinear equations.

3 Econometric Analysis

3.1 Data

The empirical analysis of the model is based on sectoral and aggregate U.S. time series at the quarterly frequency for the period 1959:1 to 2002:4. The sample period starts in 1959 because some of the data series are only available starting that year. The sample ends in 2002 because after the first half of 2003, the Bureau of Labor Statistics (BLS) stopped reporting sectoral data under the Standard Industry Classification (SIC) codes and switched to the new North American Industry Classification System (NAICS). This means that pre- and post-2003 sectoral data might not be fully comparable.

We focus on six broad sectors of the U.S. economy at the division level of the SIC, namely agriculture (Division A), mining (Division B), construction (Division C), manufacture of durable goods (Division D, Groups 24, 25, and 32 to 39), manufacture of nondurable goods (Division D, Groups 20 to 23 and 26 to 31), and services (Divisions E to I). The list of 6 sectors is exhaustive in the sense that their output aggregates to the privately-produced U.S. Gross Domestic Product (GDP).

The sectoral data consists of quarterly series on Producer Price Indices at the division level SIC, observations on yearly expenditures on labor, capital, and material inputs by each sector, and data from the U.S. Input-Output accounts. The commodity-level Producer Price Indices collected by the BLS for farm products, durable manufactured goods, and non-durable manufactured goods were used to construct sectoral inflation series for agriculture, durable manufacturing, and nondurable manufacturing, respectively.[6] Since the raw data is seasonally unadjusted, we control for seasonal effects by regressing each series on seasonal dummies and purging the seasonal components.

The data on input expenditures by each sector are used to construct estimates of the production function parameters in the manner described in Section 3.2. This data set was originally constructed by Dale Jorgenson and it is described in detail in Jorgenson and Stiroh (2000). The observations are available at the annual frequency for the years 1958 to 1996 for more than 30 sectors, but aggregation up to the division level SIC is straightforward.

Data from the U.S. Input-Output (I-O) accounts is used to construct estimates of the weights ζ_{ij} and κ_{ij}. 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 that 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.[7]

The Use Table is used to construct the weights ζ_{ij}. Use Tables contain the value in producer prices of each input used by each U.S. industry. As in Horvath (2000), the weight ζ_{ij} is computed as the share of total input expenditures by sector j that goes into inputs from

[6]The BLS only started constructing PPIs at the industry level in the mid-1980s. The three commodity-level indices mentioned above match well with their respective industries, but we were unable to find or construct similar matches for mining, construction, and services for the complete sample period.

[7]The only other year for which this is true is 1982, but documentation is more extensive and user-friendly for 1992 than for 1982.

sector i.[8] The Capital Flow Table (CFT) is used to construct the weights κ_{ij}. The CFT shows the purchases of new structures, equipment and software, allocated by using industry in producer prices. The weight κ_{ij} is computed as the share of total investment expenditures by sector j that goes into inputs from sector i. Most of the investment commodities are produced by the construction and durable manufacturing sectors, but services has non-negligible weights because this sector produces goods that are ancillary to investment, for example, engineering and landscaping services. Note that, 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.

The aggregate data consists of quarterly series on the rates of inflation, nominal money growth, and nominal interest, and per capital real money balances, investment, and consumption. With the exceptions noted below, the raw data was taken from the database of the Federal Reserve Bank of St-Louis. The inflation rate is the percentage change in the Consumer Price Index (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 the National Income and Products Accounts produced by the BEA. 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 variables were logged and detrended using a quadratic trend, except the rates of inflation (sectoral and aggregate), money growth, and nominal interest that were logged and demeaned.

[8] We equate commodities with sectors as in the theoretical model where good j is produced exclusively by sector j. This means that we are treating implicitly the Make Table of the I-O accounts as diagonal and it is the reason we can 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 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 with only one sector seems to the a reasonable approximation for the U.S. economy at this level of disaggregation.

3.2 Estimation

The model is estimated by Simulated Method of Moments (SMM). SMM has been proposed by McFadden (1989) and Pakes and Pollard (1989) to estimate discrete-choice problems, and by Lee and Ingram (1991) and Duffie and Singleton (1993) to estimate time-series models. SMM is attractive for the estimation of DSGE models for two reasons. First, the stochastic singularity of DGSE models imposes weaker restrictions on moments-based procedures than on Maximum Likelihood (ML). In particular, estimation requires the use of linearly independent moments for SMM, but linearly independent variables for 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. Second, moments-based procedures are more robust to misspecification than ML. For further discussion, see Ruge-Murcia (2003).

In order to develop the reader's intuition, consider the following comparison between SMM and calibration. In calibration, the macroeconomist computes the unconditional moments of artificial series generated by the DSGE model given the parameter values, and then compares these artificial moments with the ones estimated using actual data. The Simulated Method of Moments also compares simulated and empirical unconditional moments, but then updates the estimates of the parameter values in a manner that minimizes a well-defined measure of distance between them.

Formally, define $\mathbf{g}_t$ to be the vector of empirical observations on variables whose moments are of interest. Define $\mathbf{g}_\iota(\varphi)$ to be the synthetic counterpart of $\mathbf{g}_t$ whose elements are computed on the basis of artificial data generated by the model using parameter values φ. The sample size is denoted by T and the number of observations in the artificial time series is λT. The (optimal) SMM estimator, $\widehat{\varphi}$, is the value of φ that solves

$$\min_{\{\varphi\}} \mathbf{G}(\varphi)'\mathbf{W}\mathbf{G}(\varphi), \tag{20}$$

where

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

and $\mathbf{W}$ is the optimal weighting matrix

$$\mathbf{W} = \lim_{T\to\infty} Var\left((1/\sqrt{T})\sum_{t=1}^{T}\mathbf{g}_t\right)^{-1}. \tag{21}$$

Under the regularity conditions in Duffie and Singleton (1993),

$$\sqrt{T}(\widehat{\varphi}-\varphi) \to N(\mathbf{0},(1+1/\lambda)(\mathbf{D}'\mathbf{W}^{-1}\mathbf{D})^{-1}), \tag{22}$$

where $D = E(\partial \mathbf{g}_\iota(\varphi)/\partial\varphi)$ is a matrix assumed to be finite and of full rank.

The optimal weighting matrix, $\mathbf{W}$, is computed using the Newey-West estimator with a Barlett kernel, and the derivatives $\partial \mathbf{g}_\iota(\varphi)/\partial\varphi$ are computed numerically with the expectation approximated by the sample average of the simulated λT data points. The results reported below are based on $\lambda = 5$, meaning that the simulated series are 5 times larger than the sample size. The term $(1 + 1/\lambda)$ in (22) is a measure of the increase in sample uncertainty due to the use of simulation to compute the population moments. Using a larger value of λ permits the more accurate estimation of the simulated moments and increases the statistical efficiency of SMM, but it also increases the time required for each iteration of the minimization routine. However, sensitivity analysis indicates that the results are robust to the value of λ used.

In order to limit the effect of the starting values used to generate the artificial series, 100 extra observations were generated in every iteration of the minimization routine and the initial 100 observations were discarded. Note that the seed in the random numbers generator is fixed throughout the estimation. The use of common random draws is essential here to calculate the numerical derivatives of the minimization algorithm. Otherwise, the objective function would be discontinuous and the optimization algorithm would be unable to distinguish a change in the objective function due to a changes in the parameters from a change in the random draw used to simulate the series.

A number of parameters were estimated or calibrated prior to SMM estimation. The reason is that the estimation of this model requires the computation of the steady state and of the Blanchard-Khan solution of the model in every iteration of the optimization algorithm. The former is extremely costly computationally because it involves the solution of a large system of nonlinear equations. Thus, for estimation purposes, it is useful to distinguish between *i*) parameters that affect the dynamics of the system but not the steady state, and *ii*) parameters that determine the steady state and may or may not affect the dynamics. The latter parameters include the subjective discount rate (β), the preference parameter ς, the parameters of the sectoral production functions (α^j, ν^j, and γ^j), the parameter ψ that measures the elasticity of substitution in production and consumption, the sectoral depreciation rates (δ^j), and the consumption weights (ξ^j). An advantage of estimating these parameters beforehand is that solving (20) then requires only the computation of the model solution, but not of the steady state, in every iteration of the minimization routine.

The consumption weights, sectoral depreciation rates, and ς were taken from Horvath (2000). The parameters corresponding to our six-sector economy are reported in Columns 1 and 2 of Table 1. Horvath measures the consumption weights as the average expenditure shares in the National Income and Product Accounts from 1959 to 1995, and constructs an estimate of 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 $\widehat{\varsigma} = 0.9996$ (0.0027), where the term in parenthesis is the standard error, we set $\varsigma = 1$ in our empirical analysis.

We construct an estimate of the subjective discount rate β using the sample average of the inverse of the gross *ex-post* real interest rate, $\widehat{\beta} = 0.997$ (0.0005). By the Central Limit Theorem, this estimator is normally distributed with mean β and variance σ^2/T where $T = 175$ is the sample size and σ^2 is the variance of the π_{t+1}/R_t. The parameter ψ that measures the elasticity of substitution across goods in both consumption and production was calibrated to 2. [Explain why].

Estimates of the parameters of the production functions are constructed using the data on annual labor, capital, and material inputs expenditures for each sector collected by Dale Jorgenson for the period 1958 to 1996. The real expenditures predicted by the model may be obtained from the first-order conditions of the firm's problem,[9]

$$\nu^j \left(\Psi_t^j y_t^j\right) = \frac{w_t^j n_t^j}{P_t}, \tag{23}$$

$$\gamma^j \left(\Psi_t^j y_t^j\right) = \frac{\sum_{i=1}^{J} p_t^i h_{i,t}^j}{P_t}, \tag{24}$$

$$\alpha^j \left(\Psi_t^j y_t^j\right) = \left[\left(\frac{\Lambda_{t-1}}{\beta\Lambda_t}\right)\Omega_{t-1}^j - (1-\delta^j)\Omega_t^j\right] k_t^j + \frac{Q_t^{X^j} k_t^j}{P_t}\left(\frac{\partial\Gamma_t}{\partial k_t^j}\right). \tag{25}$$

The right-hand sides of (23) and (24) are, respectively, the wage bill and total expenditure on material inputs in sector j. The right-hand side of (25) is the total opportunity cost (net of capital gains) of the capital stock in sector j plus a term that represents the net cost of increasing the current capital stock. Jorgeson's expenditure data may be interpreted as the empirical counterpart of the right-hand side of these equations. See Jorgenson and Stiroh (2000) for details concerning the construction of this data set. Although, the data set does not contain observations on $\Psi_t^j y_t^j$, it is possible to construct estimates of α^j, ν^j, and γ^j as follows. For a given year, use two of the following three ratios: (23)/(24), (23)/(25) and (24)/(25),[10] and the condition $\alpha^j + \nu^j + \gamma^j = 1$, to obtain a system of three equations with three unknowns. The solution of this system delivers an observation of the production function parameters for that year. The estimates of α^j, ν^j, and γ^j are the sample averages of the yearly observations and their standard deviations are $\sqrt{\sigma^2/T}$ where $T = 39$ is the

[9]Note that in deriving equation (25) from first-order condition for k_{t+1}^j, we exploit the assumption of rational expectations. Thus, strictly speaking, this equation holds up to a serially uncorrelated forecast error with zero mean.

[10]Note that only two of these three ratios are linearly independent.

sample size and σ^2 is the variance of the yearly observations. These estimates are reported in Columns 3 to 5 in Table 1.

The SMM estimates of this model parameters are reported in Column 6 of Table 1 and in Table 2. The moments included in the loss function (20) are the variances and autocovariances of the variables, and the covariance between the nominal interest rate and the other variables one quarter ahead. The first set of moments allow us to exploit the information contained in the volatility and persistence of the data series. The second set of moments is included because this project is concerned specifically with the interaction between monetary and real variables. [Robustness of the results to the use of other moments].

Column 6 of Table 1 reports the SMM estimates of price rigidity in each sector. These estimates support the idea of heterogenous price rigidity at the sectoral level. While the hypothesis that $\phi^j = 0$ cannot be rejected for agriculture, mining, construction, and manufacturing, it is strongly rejected for services. Moreover, the hypothesis that price rigidity is the same in all sectors ($\phi^j = \phi$ for all j) is rejected by a [test] at the 5 per cent level.[11] Since $\phi^j = 0$ corresponds to the case of perfectly flexible prices, these results indicate that price flexibility may be a reasonable approximation in all sectors, except for services. The finding that prices are flexible in agriculture and mining is not surprising because the goods produced in these sectors are relatively homogenous and transacted in worldwide spot markets. Overall, the results are consistent with earlier research by Bils and Klenow (2004), who document substantial heterogeneity in price stickiness across goods and find that price adjustments are more frequent for goods than for services. [Cite other research that finds more price rigidity in services than other sectors].

The capital adjustment cost parameter is 9.175 (17.582). This estimate implies an elasticity of investment with respect to the price of installed capital of 5.24 [standard error].[12]. This estimate is much higher than earlier values reported by, for example, [relate of previous literature].

Finally, estimates of the autoregressive coefficients of the shock processes indicate that all shocks are fairly persistent. [Explain further and compare with results reported elsewhere].

3.3 Impulse-Response Analysis

This section examines the response of the model U.S. economy to a money supply shock. The exercise is the following: starting at steady state, the economy is subjected to an unexpected, temporary increase in the growth rate of the money supply of 1 per cent its

[11] Details on the distribution of the test and the computed statistic.

[12] The elasticity is computed as $1/(\delta\chi)$.using a depreciation rate of 0.0208. This depreciation rate corresponds to an economy-wide rate computed as the weighted average of sectoral depreciation rates.

steady state value. The dynamic responses of various aggregate and sectoral variables are plotted in Figure 1 in Panels A through L. Following the shock, there is an increase in aggregate demand that causes output, hours worked, and consumption to increase. (See Panels A, C, and E). Note, however, that these increases are not evenly spread across sectors. In particular, the output of and hours worked in construction and durable manufacturing increase proportionally more than that of other sectors, even if their prices are relatively flexible (see Panels B and D). [Relate whatever difference between Panels B and D to the different intensities across sectors]. The larger output increase in construction and durable manufacturing is be due primarily to the increase consumption on the part of firms. As firms increase output, they increase their labor demand (see Panel D) but also their demand of investment goods to build up their capital stock. However, since the production of investment goods is heavily concentrated in construction and durable manufacturing, the output of these two sectors increases proportionally more than that of other sectors.

Household consumption increases asymmetrically across sectors. The noticeable change in the composition of household consumption might be explained in part by changes in the relative prices of different goods. All prices and, consequently, the CPI rise following a positive monetary shock (see Panels G and H), but relative prices can vary substantially across sectors, as seen in Panel J. Note, for example, that the increase in household consumption of services is the smallest (even negative after the second quarter) whose relative price rises the most following a money supply shock.

Finally, notice in Panels G, I, and K, that inflation increases sharply following a money supply shock but the response of the nominal interest rate is relatively muted. This implies the substantial drop in the real interest rate plotted in Panel K.

3.4 Second Moments

This section compares the unconditional second moments predicted by the multisector model with their empirical counterparts computed using U.S. data.[13] The unconditional moments are the standard deviations, autocorrelations, and cross-correlations of seven aggregate variables, namely output, consumption, investment, real money balances, the nominal interest rate, the inflation rate, and the real wage. The moments predicted by the model are based on simulated series of 175 observations with parameter values equal to the econometric estimates reported above. The size of the simulated sample is equal to that of the U.S. data used to compute the empirical moments. In order to limit the effect of the initial obser-

[13]Note that the SMM estimates were obtained precisely by minimizing the distance between theoretical and empirical moments. Thus, [the comparison here does not have the same interpretation as in a standard calibration].

vation on the simulations, 100 extra observations were generated in every replication and then the first 100 realizations of the variables were discarded prior to the computation of the moments. The moments reported below correspond to the average of the moments obtained in 200 replications.

Table 3 reports the second moments of the U.S. data in Panel A and those predicted by the multisector model in Panel B. First, consider the standard deviations of variables. Notice that in most cases the predicted standard deviations are quantitatively close to those of the U.S. data. In particular, the multisector model generates as much investment volatility as in the data. [Compare with previous literature, including Bouakez *et al.* (2003)]. Note, however, that the model predicts a much lower interest rate volatility than found in U.S. data. [Explain why].

Second, consider the first-order autocorrelations. The multisector model replicates the persistence in output, consumption, investment and, to a lesser extent, the real wage. However, the model is less successful in capturing the autocorrelations of real balances and the rates of inflation and nominal interest. In particular, the multisector model does not capture aggregate inflation persistence. Hence, disaggregation and sectoral interaction *per se* does not solve the inflation persistence problem. In turn, this suggests that the failure of standard DSGE models to account for aggregate inflation persistence arises from modeling assumptions about price stickiness rather than from the assumption of symmetry across sectors.

Finally, consider the contemporaneous cross-correlations between the variables. In general, these correlations are broadly consistent with those observed in U.S. data. The model correctly predicts that consumption and investment are highly procyclical, while the nominal interest rate and inflation are acyclical. On the other hand, the model predicts mildly procyclical real wages but this series is acyclical in the data.

3.5 Variance Decomposition

In this section, we evaluate the relative importance of technology and monetary shocks in explaining the fluctuations in output, consumption, investment, real balances, and the rates of inflation and nominal interest. In particular, we examine the contribution of each shock to the conditional variance of the forecast error of these variables at various horizons. This variance decomposition is plotted in Figure 2. As the horizon increases, the conditional variance of the forecast error converges the unconditional variance of the variable. The decompositions of the unconditional variances are reported in Table 4.

The following results follow from Figure 2 and Table 4. *First*, money supply shocks account for most of the conditional variance in forecasting output at horizons of less than a year. At longer horizons, most of the conditional variance is due to technology shocks. In the long-run, 39 percent of the unconditional variance of output is attributed to money supply shocks, 7 percent to money demand shocks, and 54 percent to technology shocks. *Second,* money supply shocks explain most of the conditional variance in forecasting consumption at horizons of up to three years. As the horizon increases, the contribution of technology shocks increases and that of money supply shocks decreases. However, both shocks are equally important in explaining the variance of consumption in the long run. In particular, 49.9 per cent of the variance of consumption is explained by technology shocks and only 42.2 per cent by money supply shocks. *Third,* technology shocks account for the largest part of the conditional variance in forecasting investment. Although at the one-quarter horizon, the contribution of technology shocks is smaller than that of money supply shocks, the contribution of the former rises to 52 and 60 per cent at the two- and three-quarter horizons, while the contribution of money supply shocks decreases steeply. In the long run, technology shocks explain 67 of the variance of investment, compared with only 28 per cent explained by the money supply shock. *Fourth,* technology shocks explain most of the fluctuations in hours worked and inflation at all horizons. *Finally,* monetary shocks explain most of the fluctuations of the nominal interest rate. In the long-run, money supply and demand shocks explain, respectively, 43.6 and 56.4 per cent of the variance of the nominal interest rate.

4 Discussion

Table 1. Sector-Specific Parameters

	Taken from Horvath (2000)		Estimated using Jorgenson's Data Set			Estimated by SMM
Sector	ξ	δ	α	ν	γ	ϕ^j
	(1)	(2)	(3)	(4)	(5)	(6)
Agriculture	0.02	0.01	0.142*	0.261*	0.597*	0.579
			(0.005)	(0.006)	(0.006)	(1.271)
Mining	0.04	0.02	0.380*	0.243*	0.377*	2.125
			(0.009)	(0.004)	(0.011)	(21.044)
Construction	0.01	0.04	0.052*	0.394*	0.554*	2.581
			(0.001)	(0.004)	(0.005)	(58.378)
Durables	0.16	0.02	0.100*	0.321*	0.579*	13.472
			(0.001)	(0.003)	(0.002)	(15.537)
Nondurables	0.29	0.02	0.113*	0.225*	0.662*	2.265
			(0.004)	(0.002)	(0.006)	(2.231)
Services	0.48	0.02	0.222*	0.399*	0.379*	90.244*
			(0.004)	(0.003)	(0.007)	(39.725)

Notes: The consumption weights (ξ) and depreciation rates (δ) were taken from Horvath (2000, p. 87). The figures in parenthesis are standard errors. The superscript $*$ denotes the rejection of the null hypothesis that the parameter is zero at the 5 per cent significance level.

Table 2. SMM Estimates

Parameter	Model	
	Multisector	Standard
	(1)	(2)
χ	9.175	
	(17.582)	
ϕ	See Table 1	
ρ_z	0.665*	
	(0.213)	
ρ_μ	0.456*	
	(0.142)	
ρ_η	0.999*	
	(0.008)	
σ_z	0.102	
	(0.093)	
σ_μ	0.005*	
	(0.001)	
σ_η	0.005	
	(0.004)	

Notes: See notes to Table 1.

Table 3. Second Moments of Aggregate Variables

Moment	Output	Consumption	Investment	Real Balances	Interest Rate	Inflation Rate	Real Wage
			A. U.S. Data (1959:2 to 2002:4)				
S. D.	3.737	3.403	10.586	6.001	0.617	0.799	5.622
Autocorr.	0.963	0.967	0.903	0.961	0.943	0.717	0.883
Cross Corr.	1	0.957	0.686	0.759	−0.130	0.155	0.010
		1	0.530	0.839	−0.240	0.087	0.038
			1	0.362	0.219	0.246	0.188
				1	−0.283	−0.047	0.066
					1	0.652	0.015
						1	0.132
							1
			B. Multisector Model				
S. D.	4.422	3.601	11.729	8.504	0.007	1.240	3.572
Autocorr.	0.908	0.913	0.890	0.194	0.465	0.448	0.628
Cross Corr.	1	0.997	0.982	0.316	0.325	−0.051	0.441
		1	0.967	0.315	0.289	−0.073	0.430
			1	0.309	0.408	0.006	0.458
				1	0.065	−0.051	0.110
					1	0.251	0.309
						1	0.862
							1

Notes:

Table 5. Unconditional Variance Decomposition

Variable	Fraction of the Unconditional Variance Due to		
	Technology Shocks	Money Supply Shocks	Money Demand Shocks
Output	0.536	0.391	0.073
Investment	0.671	0.276	0.052
Consumption	0.499	0.422	0.079
Hours Worked	0.748	0.211	0.040
Inflation Rate	0.762	0.201	0.037
Nominal Interest Rate	0.000	0.436	0.564

Notes: Rows might not add up to one due to rounding. he money supply shock is a shock to the growth rate of the money supply. The money demand shock is a shock to the preference parameter of money in the utility function.

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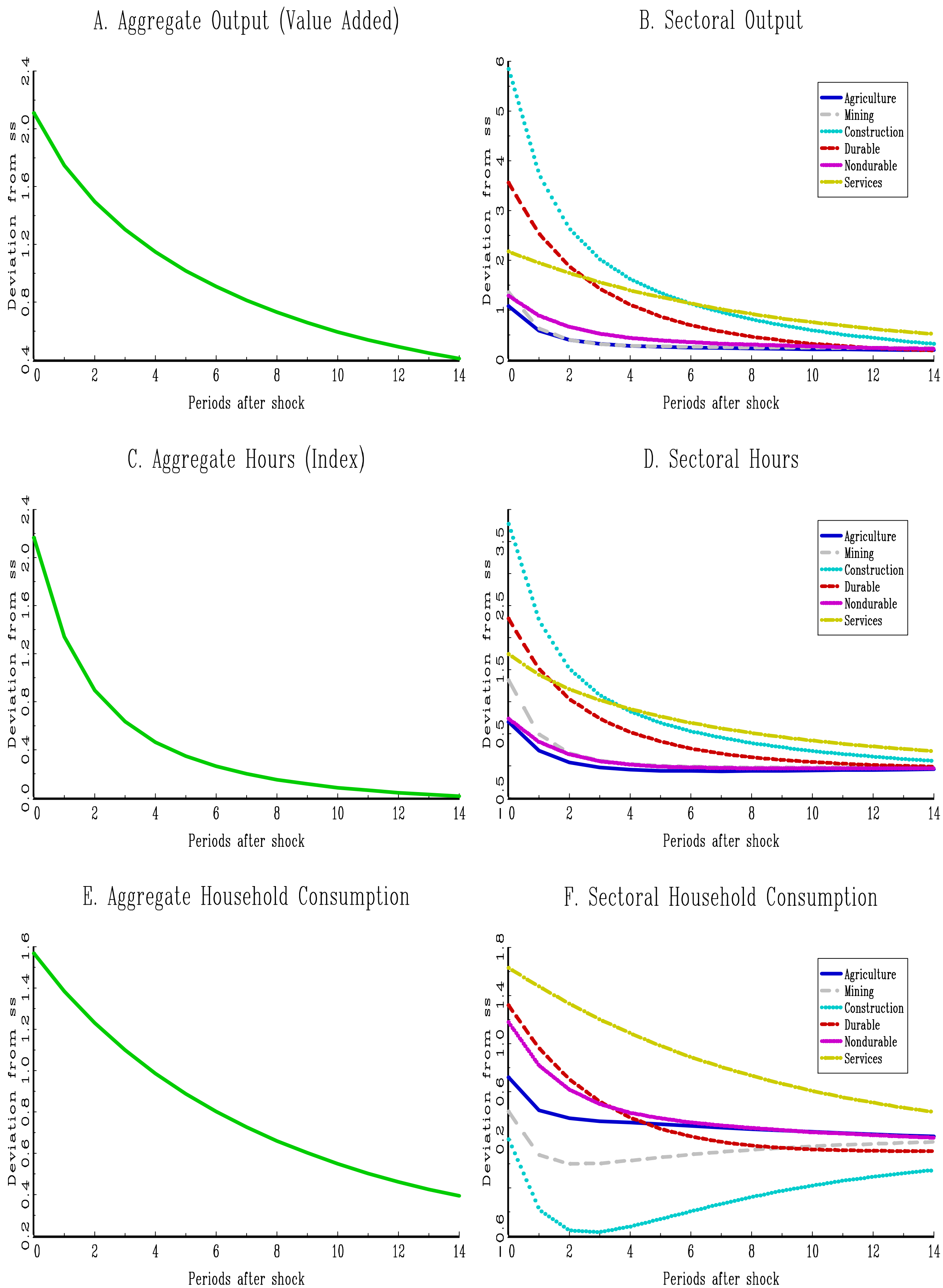
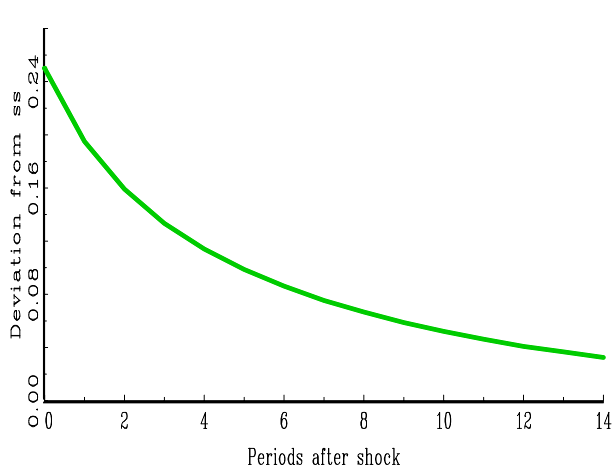
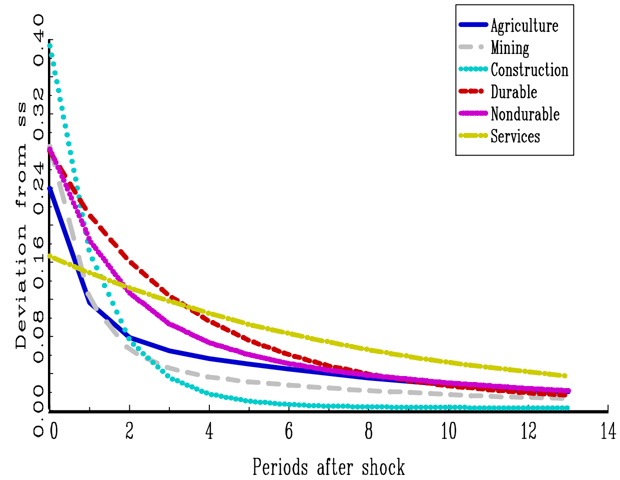

A. Aggregate Output (Value Added)
B. Sectoral Output
C. Aggregate Hours (Index)
D. Sectoral Hours
E. Aggregate Household Consumption
F. Sectoral Household Consumption
Deviation from ss
Periods after shock
Agriculture
Mining
Construction
Durable
Nondurable
Services

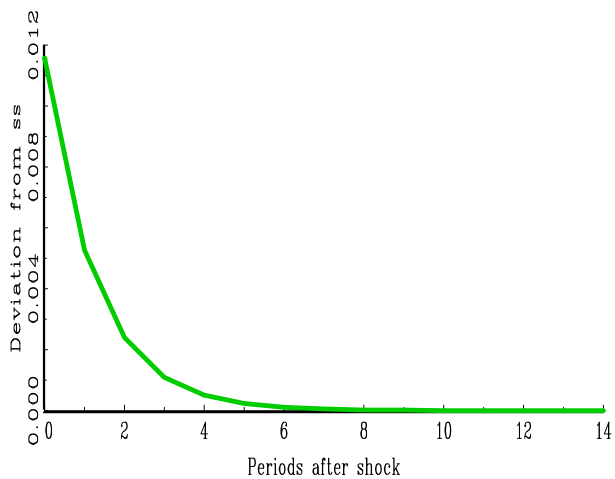
G. CPI Inflation



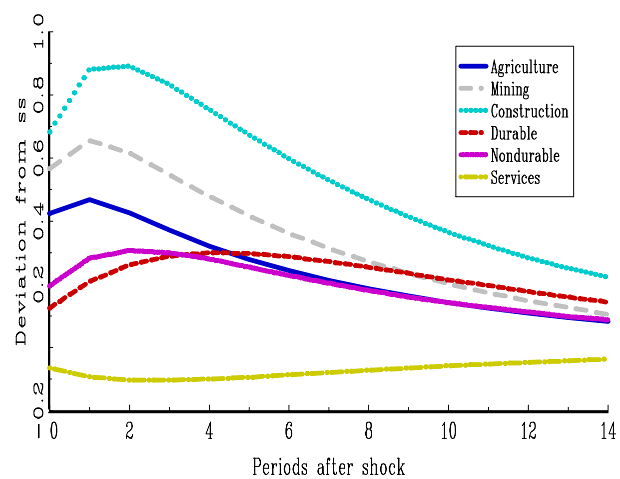
H. Sectoral Inflation



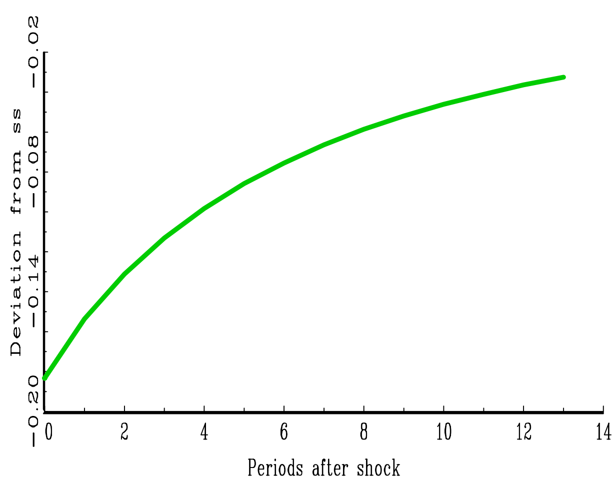
I. Nominal Interest Rate



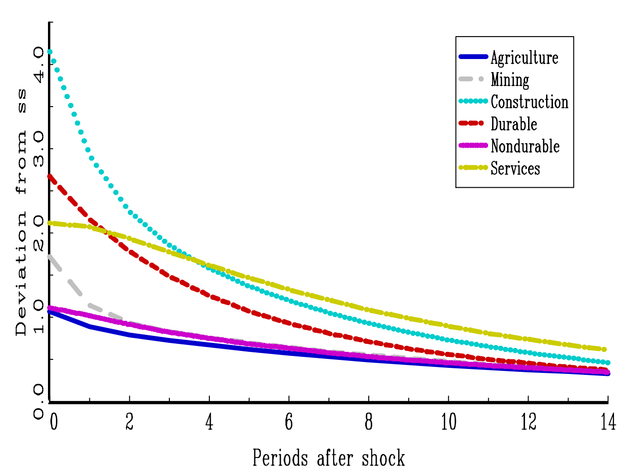
J. Relative Prices

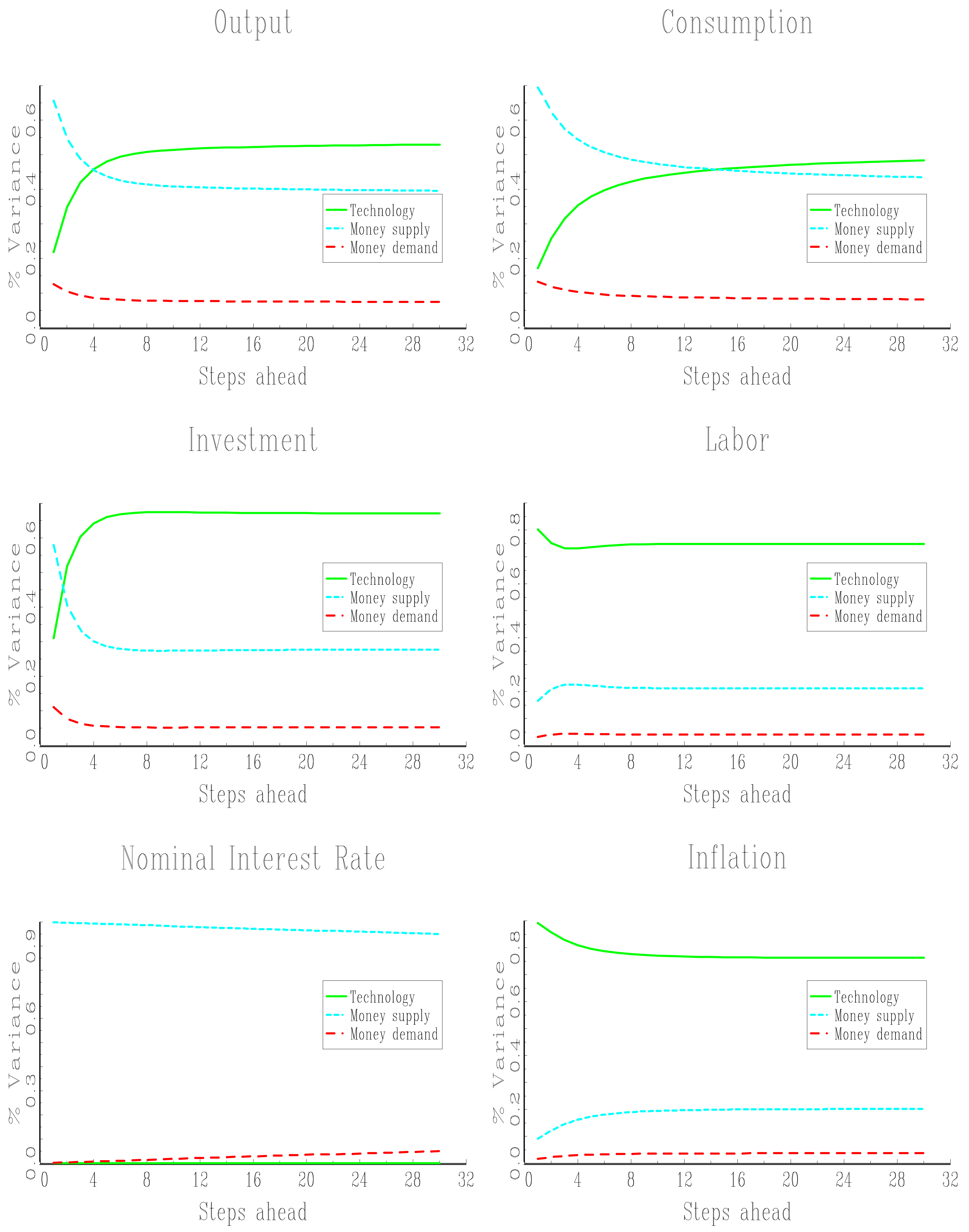


K. Real Interest Rate



L. Sectoral Wages




Output
Consumption
Investment
Labor
Nominal Interest Rate
Inflation
% Variance
Steps ahead
Technology
Money supply
Money demand
0
4
8
12
16
20
24
28
32
0
0.2
0.4
0.6
0.8
0.3
0.9