Sectoral Price Rigidity and Aggregate Dynamics*

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Abstract

The macroeconomic implications of sectoral heterogeneity are examined using a highly disaggregated multi-sector model. The model is estimated by the Simulated Method of Moments using a mix of aggregate and sectoral U.S. data. The frequencies of price changes implied by our estimates are remarkably consistent with those reported in micro-based studies, especially for non-sale prices. We study (*i*) the contribution of sectoral characteristics to the observed cross sectional heterogeneity in sectoral output and inflation responses to a monetary policy shock, (*ii*) the implications of sectoral price rigidity for aggregate output and inflation dynamics, and (*iii*) the role of sectoral shocks in explaining sectoral prices and quantities.

JEL Classification: E3, E4, E5

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1. Introduction

There is now abundant evidence from studies based on micro data that the frequency of price adjustments differs greatly across goods.[1] This heterogeneity, however, is insufficiently acknowledged in existing Neo-Keynesian models and many of its implications are not fully understood. This paper attempts to fill this gap using a highly disaggregated version of the multi-sector model developed by Bouakez, Cardia and Ruge-Murcia (2009). In that earlier paper, we were concerned with the role of input-output interactions in the transmission of monetary policy shocks and, for empirical purposes, focused on six broad sectors of the U.S. economy. The present paper undertakes the more challenging task of estimating and analyzing a 30-sector model, where the sector roughly correspond to the two-digit level of the Standard Industry Classification (SIC). As we will see, a finer level of disaggregation is essential to generate enough cross-sectional variation to formally study the micro and macroeconomic implications of heterogeneity in price rigidity.

Production sectors in the model economy differ in price rigidity, factor intensities, and productivity shocks, and are interconnected through a roundabout production structure whereby they provide materials and investment inputs to each other following the actual Input-Output Matrix and Capital Flow Table of the U.S. economy. The model parameters are estimated by the Simulated Method of Moments (SMM) using a mix of sectoral and aggregate U.S. data. Estimation results show that there is considerable heterogeneity in price rigidity across sectors, and the hypothesis that price rigidity is the same in all sectors is strongly rejected by the data. The hypothesis that prices are flexible cannot be rejected for 17 sectors, which produce primary goods (e.g., agriculture), manufactured commodities (e.g., petroleum products) and capital goods (e.g., nonelectric machinery). Conversely, the hypothesis can be rejected for 13 sectors, which produce manufactures (e.g., food products) and services.

Importantly, the frequencies of price changes implied by our estimates are generally consistent with micro-based estimates, especially for producer prices and regular consumer prices (excluding sales): the correlation between macro and micro estimates is around 0.5, and the price duration implied by our median estimate (1.5 quarters) is well within the range of durations reported in micro studies. The empirical success of standard sticky-price models generally hinges on assuming long price durations, ranging from 4 to 10 quarters, which are now considered implausible in light of the recent micro evidence on price stickiness.[2] Thus, an important contribution of this study is to demonstrate that modelling explicitly sectoral heterogeneity in price rigidity and production

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[1] See Bils and Klenow (2004), Gagnon (2007), Klenow and Kryvtsov (2008), Eichenbaum, Jaimovich and Rebelo (2008), and Nakamura and Steinsson (2008) for final goods; and Carlton (1986) for intermediate goods.

[2] See, for example, Gali and Gertler (1999), Kim (2000), Ireland (2001, 2003), Smets and Wouters (2003), Christiano, Eichenbaum and Evans (2005), and Bouakez, Cardia and Ruge-Murcia (2005).

technology can help reconcile Neo-Keynesian models with the micro data.

With the estimated model in hand, we study the implications of sectoral heterogeneity in price rigidity along two dimensions: the extent to which it accounts for the sectoral effects of monetary policy, and its importance for aggregate fluctuations. Regarding the former, our results indicate that the heterogeneity in price stickiness is the primary factor explaining the heterogeneity in sectoral inflation responses to a monetary policy shock. In contrast, the heterogeneity in sectoral output responses is mainly driven by whether or not the sectors produce capital goods and by materials intensity. Capital-good sectors adjust their output by more than nondurable-goods sector and this is so regardless of whether their prices are flexible or rigid. This result reflects the sparsity of the actual Capital-Flow Table whereby the production of capital goods is concentrated in a small number of sectors. The presence of materials (or intermediate) inputs amplifies the output effects of monetary policy shocks, as shown theoretically by Basu (1995) using a stylized roundabout production economy. Our analysis quantifies this amplification effect in the context of a realistic model, but, in addition, shows that it is statistically significant only to the extent that one allows for heterogeneity in price stickiness across sectors. Indeed, an otherwise identical model in which prices are assumed to be equally rigid across sectors implies that materials intensity is no longer an important determinant of the cross-sectional heterogeneity in output responses to a monetary policy shock.

Regarding the aggregate implications of sectoral heterogeneity in price rigidity, we first show that the dispersion in sectoral inflation rates predicted by the model induces substantial persistence in the aggregate inflation rate. This result is important inasmuch as standard sticky-price models generally generate a much lower aggregate inflation persistence than found in the data, and thus ad-hoc mechanisms (for example, rule-of-thumb producers) are used to remedy this shortcoming of forward-looking pricing rules. Second, we show that modeling heterogeneity in price rigidity has critical implications regarding the relative importance of the various shocks in business cycle fluctuations. The version of the model with identical price rigidity in all sectors attributes most (90 percent) of the unconditional variance of output to sectoral productivity shocks and only 5 percent to the monetary policy shock. Instead, the model with heterogenous price rigidly attributes most of the unconditional variance of output to an aggregate labor supply shock (64 percent), a substantial proportion to the monetary policy shock (24 percent) and a small proportion to sectoral shocks.[3]

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[3] In two related papers, Carvalho (2006) and Nakamura and Steinsson (2010) also study the role of heterogeneity in price rigidity as an amplification mechanism of the effects of montary policy shocks on aggregate output, though in more restricted envorionments. Both papers abstract from capital accumulation; Carvalho abstracts from materials inputs as well, while Nakamura and Steinsson model materials inputs symmetrically, in that firms in a given sector use equal proportions of all goods. In addition, both papers calibrate the parameters using the micro data and evaluate the model in terms of their macro predictions. Instead, this paper delivers independent estimates of the structural

The model is also used to study the role of sectoral productivity shocks. A key result of our analysis is that while these shocks are essentially irrelevant to aggregate fluctuations, they are nonetheless crucial to understand sectoral dynamics: They account for a substantial part of the variance of sectoral inflation, real prices and marginal costs, and a nontrivial part of the variance of sectoral output. This result suggests that sectoral shocks are an important cause of the price changes observed at the micro level and that the observed volatility in sectoral inflation rates need not imply that money is neutral. Boivin, Giannoni, and Mihov (2007) and Mackowiak, Moench, and Wiederholt (2009) examine this question using statistical factor models where the idiosyncratic component is basically a residual term. Instead, our structural analysis puts an economic label on the source of sector-specific shocks and traces out their effects through a fully-specified economy. For example, our analysis shows that shocks to agriculture and oil production have large effects on other sectors as a result of input-output interactions.

The paper is organized as follows: Section 2 presents the model; Section 3 discusses a number of econometric issues and our estimation strategy; Section 4 reports parameter estimates and examines the microeconomic implications of the model; Section 5 studies implications of heterogeneity in price rigidity; Section 7 documents the importance of sectoral shocks for the dynamics of sectoral variables; and, finally, Section 7 summarizes the main conclusions and results from our analysis.

2. A Multi-Sector Model with Heterogenous Production Sectors

The analytical framework used to study the sectoral data is that developed in our previous work (see Bouakez, Cardia, and Ruge-Murcia, 2009). Thus, in order to save space, we present here only the outline of the model and refer the reader to that article for a more detailed discussion of modelling assumptions and functional forms.

2.1 Production and Intermediate Consumption

Production is carried out by continua of firms in each of J sectors. Firms in the same sector are identical except for the fact that their goods are differentiated and, consequently, they have monopolistically competitive power. In contrast, firms in different sectors have different production functions, use different combinations of materials and investment inputs, and face different nominal price frictions. Firm l in sector j produces output y_t^{lj} using the technology

$$y_t^{lj} = (z_t^j n_t^{lj})^{\nu^j} (k_t^{lj})^{\alpha^j} (H_t^{lj})^{\gamma^j}, \tag{1}$$

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parameters and evaluates the model both in terms of its micro and macro predictions.

where z_t^j is a sector-specific productivity shock, n_t^{lj} is labor, k_t^{lj} is capital, H_t^{lj} is materials inputs, and $\nu^j + \alpha^j + \gamma^j = 1$. The sectoral productivity shock follows the process

$$\ln(z_t^j) = (1 - \rho_{z^j}) \ln(z_{ss}^j) + \rho_{z^j} \ln(z_{t-1}^j) + \epsilon_{z^j,t},$$

where $\rho_{z^j} \in (-1, 1)$, $\ln(z_{ss}^j)$ is the unconditional mean, and the innovation $\epsilon_{z^j,t}$ is identically and independently distributed (*i.i.d.*) with zero mean and variance $\sigma_{z^j}^2$.[4]

Materials inputs are a composite of goods produced by all firms in all sectors:

$$H_t^{lj} = \prod_{i=1}^{J} \zeta_{ij}^{-\zeta_{ij}} (h_{i,t}^{lj})^{\zeta_{ij}}, \tag{2}$$

where $\zeta_{ij} \geq 0$ is a weight, such that $\sum\limits_{i=1}^{J} \zeta_{ij} = 1$,

$$h_{i,t}^{lj} = \left(\int_0^1 \left(h_{mi,t}^{lj} \right)^{(\theta-1)/\theta} dm \right)^{\theta/(\theta-1)}, \tag{3}$$

$h_{mi,t}^{lj}$ is the quantity of good produced by firm m in sector i that is purchased by firm l in sector j as materials input, and $\theta > 1$ is the elasticity of substitution between goods produced in the same sector. The capital stock is directly owned by firms and follows the law of motion

$$k_{t+1}^{lj} = (1 - \delta) k_t^{lj} + X_t^{lj}, \tag{4}$$

where $\delta \in (0, 1)$ is the depreciation rate and X_t^{lj} is an investment technology that combines different goods into units of capital. In particular,

$$X_t^{lj} = \prod_{i=1}^{J} \kappa_{ij}^{-\kappa_{ij}} (x_{i,t}^{lj})^{\kappa_{ij}}, \tag{5}$$

where $\kappa_{ij} \geq 0$ is a weight, such that $\sum\limits_{i=1}^{J} \kappa_{ij} = 1$,

$$x_{i,t}^{lj} = \left(\int_0^1 \left(x_{mi,t}^{lj} \right)^{(\theta-1)/\theta} dm \right)^{\theta/(\theta-1)}, \tag{6}$$

and $x_{mi,t}^{lj}$ is the quantity of good produced by firm m in sector i that is purchased by firm l in sector j for investment purposes. The prices of the composites H_t^j and X_t^j are $Q_t^{H^j} = \prod\limits_{i=1}^{J} (p_t^i)^{\zeta_{ij}}$

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[4] Idiosyncratic productivity shocks are also assumed by Golosov and Lucas (2007), Gertler and Leahy (2008) and Midrigan (2008). In those models all shocks are drawn from the same distribution, while in our model the shock distribution depends on the sector to which the firm belongs.

and $Q_t^{X^j} = \prod_{i=1}^{J} (p_t^i)^{\kappa_{ij}}$, respectively, where

$$p_t^i = \left(\int_0^1 (p_t^{mi})^{1-\theta} dm \right)^{1/(1-\theta)}, \tag{7}$$

and p_t^{mi} is the price of the good produced by firm m in sector i.

Firms face convex costs when adjusting their capital stock and nominal price. Capital-adjustment costs are proportional to the current capital stock and take the quadratic form

$$\Gamma_t^{lj} = \Gamma(X_t^{lj}, k_t^{lj}) = \frac{\chi}{2} \left(\frac{X_t^{lj}}{k_t^{lj}} - \delta \right)^2 k_t^{lj}, \tag{8}$$

where $\chi \geq 0$. Similarly, the real per-unit cost of changing the nominal price is

$$\Phi_t^{lj} = \Phi(p_t^{lj}, p_{t-1}^{lj}) = \frac{\phi^j}{2} \left(\frac{p_t^{lj}}{\pi_{ss} p_{t-1}^{lj}} - 1 \right)^2, \tag{9}$$

where p_t^{lj} is the price of the good produced by firm l in sector j, $\phi^j \geqslant 0$ is a sector-specific parameter, and π_{ss} is the steady-state aggregate inflation rate. The quadratic adjustment-cost model for nominal prices is due to Rotemberg (1982).[5] In the special case where $\phi^j = 0$, the prices of goods produced in sector j are flexible. In this model, there are neither temporary sales nor volume discounts. Also, since the price elasticity of demand does not depend on the use given to the good by the buyer, firms charge the same price to all consumers regardless of whether their output is used as investment good, consumption good, or materials input.

The firm's problem is to maximize

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{t-\tau} \left(\frac{\Lambda_\tau}{\Lambda_t} \right) \left(\frac{d_t^{lj}}{P_t} \right), \tag{10}$$

where d_t^{lj} are nominal profits, P_t is the aggregate price index (to be defined below), $\beta \in (0,1)$ is a discount factor and Λ_t is the consumers' marginal utility of wealth. Nominal profits are

$$\begin{aligned} d_t^{lj} = {} & p_t^{lj} \left(c_t^{lj} + \sum_{i=1}^{J} \int_0^1 x_{lj,t}^{mi} dm + \sum_{i=1}^{J} \int_0^1 h_{lj,t}^{mi} dm \right) - w_t^{lj} n_t^{lj} - \sum_{i=1}^{J} \int_0^1 p_t^{mi} x_{mi,t}^{lj} dm - \sum_{i=1}^{J} \int_0^1 p_t^{mi} h_{mi,t}^{lj} dm \\ & - \Gamma_t^{lj} Q_t^{X^j} - \Phi_t^{lj} p_t^{lj} \left(c_t^{lj} + \sum_{i=1}^{J} \int_0^1 x_{lj,t}^{mi} dm + \sum_{i=1}^{J} \int_0^1 h_{lj,t}^{mi} dm \right), \end{aligned} \tag{11}$$

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[5] We use this model rather than the Calvo model because aggregation is simpler: There are no price cohorts and the equilibrium is, therefore, symmetric within sectors. In Section 4.1, we exploit the functional equivalence between the sectoral Phillips curves implied by both models to help interpret our empirical estimates of ϕ^j.

where c_t^{lj} is final consumption, w_t^{lj} is the nominal wage, and $x_{lj,t}^{mi}$ and $h_{lj,t}^{mi}$ are respectively the quantities sold to firm m in sector i as materials input and investment good. Profit maximization delivers the following demand functions for materials and investment inputs:

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

2.2 Final Consumption

Consumers are identical, infinitely lived, and their number is constant and normalized to one. The representative consumer maximizes

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{t-\tau} U\left(C_t, M_t/P_t, 1-N_t\right), \tag{12}$$

where $U(\cdot)$ is an instantaneous utility function that satisfies the Inada conditions and is assumed to be strictly increasing in all arguments, strictly concave and twice continuously differentiable, C_t is consumption, M_t is the nominal money stock, N_t is hours worked, and the time endowment has been normalized to 1.

Consumption is an aggregate of all available goods:

$$C_t = \prod_{j=1}^{J} (\xi^j)^{-\xi^j} (c_t^j)^{\xi^j}, \tag{13}$$

where ξ^j is a nonnegative weight that satisfies $\sum_{j=1}^{J} \xi^j = 1$ and

$$c_t^j = \left(\int_0^1 \left(c_t^{lj}\right)^{(\theta-1)/\theta} dl\right)^{\theta/(\theta-1)}, \tag{14}$$

with c_t^{lj} the final consumption of the good produced by firm l in sector j. As in Horvath (2000), hours worked are an aggregate of the hours supplied to each firm in each sector:

$$N_t = \left(\sum_{j=1}^{J} (n_t^j)^{(\varsigma+1)/\varsigma}\right)^{\varsigma/(\varsigma+1)}, \tag{15}$$

where $\varsigma > 0$ is a constant parameter and $n_t^j = \int_0^1 n_t^{lj} dl$ is the number of hours worked in sector j, with n_t^{lj} being the number of hours worked in firm l in sector j. This specification is a simple way to model imperfect labor mobility across sectors and allow different wages and hours in different sectors. The aggregate price index is defined as

$$P_t = \prod_{j=1}^{J} (p_t^j)^{\xi^j}, \tag{16}$$

where $p_t^j = \left(\int\limits_0^1 (p_t^{lj})^{1-\theta} dl \right)^{1/(1-\theta)}$.

In the rest of the paper, we specialize the instantaneous utility function to

$$U\left(C_t, M_t/P_t, 1-N_t\right) = \log(C_t) + \upsilon_t \log(M_t/P_t) + \eta_t \log(1-N_t), \tag{17}$$

where υ_t and η_t are preference shocks. These shocks disturb the intratemporal first-order conditions that determine money demand and labor supply, respectively, and follow the processes

$$\begin{aligned} \ln(\upsilon_t) &= (1-\rho_\upsilon)\ln(\upsilon_{ss}) + \rho_\eta \ln(\upsilon_{t-1}) + \epsilon_{\upsilon,t}, \\ \ln(\eta_t) &= (1-\rho_\eta)\ln(\eta_{ss}) + \rho_\eta \ln(\eta_{t-1}) + \epsilon_{\eta,t}, \end{aligned}$$

where $\rho_\upsilon, \rho_\eta \in (-1,1)$, $\ln(\upsilon_{ss})$ and $\ln(\eta_{ss})$ are unconditional means, and the innovations $\epsilon_{\upsilon,t}$ and $\epsilon_{\eta,t}$ are *i.i.d.* with zero mean and variances σ_υ^2 and σ_η^2, respectively.

The consumer's budget constraint (in real terms) is

$$\begin{aligned} \sum_{j=1}^{J} \int\limits_0^1 \left(\frac{p_t^{lj} c_t^{lj}}{P_t} \right) dl + b_t + m_t + \sum_{j=1}^{J} \int\limits_0^1 \left(\frac{a_t^{lj} s_t^{lj}}{P_t} \right) dl \quad &= \quad \sum_{j=1}^{J} \int\limits_0^1 \left(\frac{w_t^{lj} n_t^{lj}}{P_t} \right) dl + \frac{R_{t-1} b_{t-1}}{\pi_t} + \frac{m_{t-1}}{\pi_t} \\ &\quad + \sum_{j=1}^{J} \int\limits_0^1 \left(\frac{(d_t^{lj} + a_t^{lj}) s_{t-1}^{lj}}{P_t} \right) dl + \frac{\Upsilon_t}{P_t}, \end{aligned}$$

where b_t is the real value of nominal bond holdings, $m_t = M_t/P_t$ is real money balances, 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, s_{t-1}^j shares in a sectoral mutual fund, 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 consumer's utility maximization determines the demand for the good produced by firm l in sector j

$$c_t^{lj} = \xi^j \left(\frac{p_t^{lj}}{p_t^j} \right)^{-\theta} \left(\frac{p_t^j}{P_t} \right)^{-1} C_t. \tag{18}$$

2.3 Fiscal and Monetary Policy

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

$$\Upsilon_t/P_t = m_t - m_{t-1}/\pi_t, \tag{19}$$

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, which follows the process

$$\ln(\mu_t) = (1 - \rho_\mu)\ln(\mu_{ss}) + \rho_\mu \ln(\mu_{t-1}) + \epsilon_{\mu,t},$$

where $\rho_\mu \in (-1, 1)$, $\ln(\mu_{ss})$ is the unconditional mean, and the innovation $\epsilon_{\mu,t}$ is *i.i.d.* with zero mean and variance σ^2_μ.

2.4 Aggregation and Equilibrium

In equilibrium, net private bond holdings equal zero because consumers are identical, the total share holdings in sector j add up to one, and firms in the same sector are identical. Appendix A shows that

$$\sum_{j=1}^{J} Y_t^j = P_t C_t + \sum_{j=1}^{J} Q_t^{X^j} X_t^j + \sum_{j=1}^{J} A_t^j. \tag{20}$$

That is, aggregate output equals private consumption plus investment and the sum of all adjustment costs in all sectors, where aggregate output in our model is measured as the sum of sectoral values added, just as in the U.S. National Income and Product Accounts.

The equilibrium of the model is symmetric within sectors but asymmetric between sectors. Thus, relative sectoral prices are not all equal to one and real wages and allocations are different across sectors. The model is solved numerically by log-linearizing its equilibrium conditions around the deterministic steady state and applying standard techniques to solve the resulting system of stochastic linear difference equations.

3. Estimation Issues

3.1 Disaggregation Level

The multi-sector model is used to study a highly disaggregated version of the U.S. economy with thirty sectors that roughly correspond to the two-digit Standard Industrial Classification (SIC).

The sectors are listed in Table 1 along with the Major Group categories that they include. Agriculture includes the production of crops and livestock, agriculture-related services, and forestry. Construction includes building and heavy construction and special trade contractors. The four mining sectors are Major Groups 10 and 12 to 14. The twenty manufacturing sectors are Major Groups 20 to 39. Transport and utilities includes all forms of passenger and freight transportation, communications, and electric, gas and sanitary services. Trade includes both wholesale and retail trade. FIRE is finance, insurance and real estate. Finally, other services includes personal, business, recreation, repair, health, legal, educational and social services as well as lodging. At this level of disaggregation, agriculture, mining and construction all include some service industries. For example, oil and gas extraction includes drilling and exploration services.

3.2 Estimation Strategy

The model is estimated by the Simulated Method of Moments (SMM) using sectoral and aggregate U.S. time series at the quarterly frequency for the period 1964Q1 to 2002Q4.[6] The sample starts in 1964 because data on wages in the service sector are available only after this date, and ends in 2002 because thereafter the BLS stopped reporting sectoral data under the SIC codes.

The sectoral data consist of quarterly series of real wages and PPI (Producer Price Index) inflation rates, computed using raw data taken from the BLS web site (*www.bls.gov*). Unfortunately, these data are not available for all thirty sectors in our model. We use sectoral wages for construction, all manufacturing sectors (except electric machinery and instruments for which the data are not available for the complete sample period) and all services sectors. Sectoral wages 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.

We use sectoral inflation for the fourteen sectors listed in Table 2 for which it is possible to match commodity-based PPIs with their respective sector. Matching commodity-based PPIs with sectors allows us to address the fact that the BLS only started to construct industry-level PPIs in the mid-1980s. We assess the quality of the match by computing the correlation between the inflation rates constructed using commodity-based and industry-level PPIs for the periods where both index types are available. These correlations are reported in Table 2 and vary between 0.59

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[6] In this application, the length of the simulated series relative to the sample size is 20 and the weighting matrix 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 latter is computed using the Newey-West estimator with a Barlett kernel and Newey-West fixed bandwidth, that is, the integer of $4(T/100)^{2/9}$ where T is the sample size, but results are reasonably robust to using other bandwidths. For the model simulation innovations are drawn from normal distributions. See Ruge-Murcia (2007) for a detailed explanation of the application of SMM to the estimation of DSGE models and Monte-Carlo evidence on its small-sample properties.

for oil and natural gas to almost 1 for tobacco products.[7] Notice 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 and other sectoral variables through general equilibrium effects. 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 from the Federal Reserve Bank of St-Louis web site (*www.stls.frb.org*). 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. These 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 the 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.

In summary, the moments used to estimate the model are the variances and first-order autocovariances of the following 43 series: per-capita consumption, investment and real money balances; the rates of money growth, nominal interest, and CPI inflation; the rates of PPI inflation in agriculture, coal mining, oil and gas extraction, nonmetallic mining, food products, tobacco products, lumber and wood, furniture and fixtures, paper, chemicals, oil refining, rubber and plastics, leather, and stone, clay and glass; and the real wages in construction, all twenty manufacturing sectors (except for electric machinery and for instruments) and all four service sectors. These 86 moments are used to identify 47 structural parameters. The parameters are 30 sectoral price rigidities, the capital adjustment cost parameter, and the autocorrelation and standard deviation of the productivity, money demand, labor supply and monetary policy shocks. Estimating both parameters of

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[7] We were unable to compute this correlation for agriculture because no industry-level PPI is available. In preliminary work, we considered using the commodity-based PPI for metals but the correlation with its industry-level equivalent was only 0.15.

the productivity-shock processes for all sectors would mean estimating 60 parameters. Hence, in order to economize degrees of freedom and sharpen identification, we limit shock heterogeneity to the Division level of the SIC. Thus, we assume one distribution each for agriculture (Division A), all mining sectors (Division B), construction (Division C), all manufacturing sectors (Division D), and all services sectors (Divisions E through I). This means that we estimate the parameters of five rather than of thirty shock distributions. Since draws are independent, however, shock realizations will be different in different sectors, whether they are in the same Division or not.

Since finding the steady state of model requires solving a large system of nonlinear equations, estimation is computationally intensive and practically unfeasible. To circumvent this difficulty, we calibrate the parameters that determine the steady state. The discount rate (β) is set to 0.997, which is the sample average of the inverse of the gross ex-post real interest rate for the period 1964Q2 to 2002Q4. The depreciation rate is set to $\delta = 0.02$. The elasticity of substitution between goods produced in the same sector (θ) is set to 8. This value is in the middle of the range used in the literature, and implies an average markup over marginal cost of approximately 15 percent. The parameter that determines the elasticity of substitution between hours worked in different sectors is set to 1 (see Horvath, 2000). The consumption weights $\left(\xi^j\right)$ are the average expenditure shares in NIPA from 1959 to 1995 and were taken from Horvath (2000, p. 87).[8] The input weights ζ_{ij} and κ_{ij} are equal to the share of sector i in the materials and investment input expenditures by sector j, respectively. These shares are computed using data from the 1992 U.S. Input-Output (I-O) accounts.[9] More precisely, the ζ_{ij}s are computed using the Use Table, which contains the value of each input used by each U.S. industry, while the κ_{ij}s are computed using the Capital Flow Table, which reports the purchases of new structures, equipment and software allocated by using industry.

The production function parameters are calibrated on the basis of estimates obtained using the sectoral data on input expenditures compiled by Dale Jorgenson.[10] The estimates are reported in Table 1 and indicate substantial heterogeneity in capital, labor and materials intensities across sectors. Services sectors, especially trade, tend to be labor intensive but so are also construction, coal mining and some manufacturing sectors like instruments, and printing and publishing. Mining sectors are generally the most capital intensive of the economy, while construction is the least

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[8] Our sector definitions differ from Horvath's in that we respectively combine into one sector: agricultural products and agricultural services; motor vehicles and transportation equipment; and transportation services, communications, electric and gas utilities, and water and sanitary services.

[9] I-O tables do evolve over time, for example as a result of technological innovation, but the change is relatively moderate at the level of disaggregation used here. We carried out a small number of sensitivity experiments and found our results to be robust to small perturbations around the values used.

[10] See Appendix B for a description of the methodology used to construct these estimates.

capital intensive. Materials intensity tends to be relatively low in services and mining compared with manufacturing, construction and agriculture. Some manufacturing sectors like oil refining, food products, textile mill products, and lumber and wood are extremely intensive in materials. This heterogeneity in production function parameters is statistically significant in that tests of the null hypothesis that ν^j, γ^j and α^j are equal in all sectors are strongly rejected by the data.

4. Parameter Estimates

In this section, we report SMM estimates of the structural parameters of the model and, in particular, compare our estimates of sectoral price rigidity and productivity with those based on micro data. We also report SMM estimates for a benchmark version of the model where price rigidity is the same in all sectors.

4.1 Sectoral Price Rigidity

SMM estimates of the price rigidity parameters are reported in Table 3. The magnitude of this parameter varies greatly across sectors and the null hypothesis that its true value is the same in all sectors is strongly rejected by the data (p-value < 0.0001). Hence, heterogeneity in price rigidity is quantitatively important and statistically significant.

The median price rigidity parameter is only 4.80, which implies a median price duration of only 1.5 quarters (see below). This estimate is in the range of median price durations reported in micro-based studies. For example, the median price duration varies between 1.4 and 1.8 quarters in Bils and Klenow (2004), between 1.2 and 2.4 in Klenow and Kryvtsov (2008), and between 1.4 to 3.6 quarters in Nakamura and Steinsson (2008). In turn, all of these estimates are generally smaller than those obtained using aggregate data alone. For example, Gali and Gertler (1999), Smets and Wouters (2003), and Bouakez, Cardia and Ruge-Murcia (2005) respectively report "aggregate" price durations of 5.9, 10.5, and 6.5 quarters. Large price rigidity estimates contribute to the empirical success of one-sector Neo-Keynesian DSGE models, but those estimates are now regarded by some as implausible in light of the recent micro evidence on price rigidity. Instead, our heterogenous multi-sector DSGE model delivers price durations in line with micro data but substantial monetary policy effects (see Section 4). In this sense, our model helps reconcile Neo-Keynesian models with the micro data.

The hypothesis that prices are flexible (that is, $\phi = 0$) cannot be rejected at the 5 percent level for 17 out of 30 sectors in our sample. Thus, at this level of disaggregation, the majority of sectors in the U.S. economy are flexible-price sectors. Flexible-price sectors include producers of primary goods (agriculture and mining), manufactured commodities (for example, tobacco, chemical and petroleum products) and some capital goods (for example, electric and nonelectric machinery, and instruments). Conversely, the hypothesis that $\phi = 0$ can be rejected for 13 sectors, but the magnitude of ϕ is especially large in eight sectors, namely trade, transport and utilities, primary metal, construction, food, apparel, furniture, and leather goods. Importantly, the first two sectors (trade, and transport and utilities) are services and account for a substantial part of the Consumer Price Index. Hence, these results suggest that price rigidity in the U.S. economy is mostly concentrated in services.

We now compare our macro estimates of sectoral price rigidity with estimates computed by Bils and Klenow (2004) and Nakamura and Steinsson (2008) using U.S. micro data. In order to make this comparison we exploit the observational equivalence between the Phillips curves in the (log-linearized) Rotemberg and Calvo models and compute the Calvo probabilities and average price durations implied by our estimates (see Appendix C). These implied probabilities and durations are reported in Table 3.

Durations constructed from the micro-based estimates are also reported in Table 3. The mean durations for producer prices were computed as the inverse of the monthly frequencies of price changes for Major Industries reported by Nakamura and Steinsson (see their Table 7), divided by 3 to express them in quarters.[11] The mean durations of consumer prices were estimated as follows. First, each Entry Level Item (ELI) category in the micro data was matched into one of our sector definitions. Then, sectoral price durations were computed as the weighted average of the durations of ELIs in that sector. The raw ELI durations are those reported by Bils and Klenow (2004) and Nakamura and Steinsson (2008), and the weights are proportional to those given to each ELI in the CPI.[12] In total, we constructed four sets of micro estimates respectively based on PPI prices, regular CPI prices and final CPI prices from Nakamura and Steinsson, and final CPI prices from Bils and Klenow. Final CPI prices include the effect of sales.

A graphic comparison between the durations implied by the estimated DSGE model and those computed from micro data is reported in Figure 1. Along the continuos 45 degree line estimates would match perfectly. Observations marked with a "plus" ("circle") are macro-based durations

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[11] Nakamura and Steinsson use different sector definitions from ours, so we match the sectors closest in nature. However, they respectively combine primary and fabricated metal, and electric and nonelectric machinery into single categories. Given the ambiguity in matching these sectors, we have dropped them from Table 3.

[12] There were some ELIs for which there was no obvious sectoral match and, consequently, were excluded from the analysis. These were 8 out of 272 ELIs in Nakamura and Steinsson, and 26 out of 350 in Bils and Klenow. Another issue is that the number of ELIs per sector varies considerably. For example, in Bils and Klenow's data, there are 79 ELIs corresponding to food products, but only 2 corresponding to fabricated metal. This means that not all sectoral mean durations are equally accurate. In order the limit the effect of estimates based on too few ELIs, we restricted the analysis to estimates constructed using at least five ELIs. The only exception is tobacco products where cigarettes and cigars account for most of the sectoral output.

for which the null hypothesis that their true value equals the micro-based estimate cannot (can) be rejected at the 5 percent significance level. Although there are outliers in all panels, this figure shows that both sets of estimates are in broad quantitative agreement. Furthermore, the figure has many more "pluses" than "circles," meaning that micro and macro estimates are statistically the same for most sectors. This result is remarkable given the large methodological differences between the two approaches.

Notice in Figure 1 that macro estimates are better correlated with micro estimates based on PPI and regular CPI prices than with those based on final CPI prices that include sales. The correlation between macro estimates and micro estimates based on PPI (regular CPI) prices is 0.49 (0.49) and statistically different from zero. In contrast, the correlation between macro estimates and final CPI prices, which include sales, is close to zero. These results are not surprising since our model and data abstract from transitory sales. Moreover, these results are consistent with what we observe when we compare micro-based estimates among themselves. The correlation between durations based on PPI and regular CPI prices is high (0.78) and statistically different from zero,[13] but the correlation between either of them and durations based on final prices is low and not statistically different from zero.

4.2 Other Parameter Estimates

Table 4 reports SMM estimates of the other structural parameters. The estimate of the capital adjustment cost parameter is 4.71 (3.80), where the term in parenthesis is the standard error. This estimate is not statistically different from zero and is quantitatively smaller than values reported in previous literature that estimates χ using aggregate data alone (see, for example, Kim, 2000, and Bouakez, Cardia and Ruge-Murcia, 2005). The reason is that in our model, input-output interactions induce strategic complementarity in pricing across sectors and greatly amplify the effects of monetary shocks, thereby reducing the quantitative importance of other real rigidities, like capital adjustment costs.

Labor supply and money demand shocks are relatively persistent and feature volatile innovations, while monetary policy shocks are only mildly persistent and not very volatile. In particular, the estimated autoregressive coefficient is 0.46 (0.07), which is smaller than, but still consistent with, the estimate that would be obtained from an unrestricted first-order autoregression of the rate of growth of money supply, which is 0.58 (0.09).[14]

The autoregressive coefficient of productivity shocks varies from 0.83 in mining to 0.95 in man-

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[13] This correlation is similar to one of 0.83 between the frequency of price changes for producer and regular consumer prices reported by Nakamura and Steinsson (2008) and which is computed using 153 goods categories.

[14] This estimate was computed by OLS using the rate of growth of M2 for the sample period 1964Q2 to 2002Q4.

ufacturing, but the null hypothesis that these values are the same in all sectors cannot be rejected at the 5 percent level. In contrast, there is substantial heterogeneity in the standard deviation of productivity innovations across sectors. Estimates range from 0.02 in services to 0.11 in agriculture and the null hypothesis that standard deviations are the same in all sectors can be rejected at the 5 percent level. In general, productivity innovations in primary sectors (agriculture and mining) are substantially more volatile than in other sectors.

Our results are similar to those in Horvath (2000), who also finds innovations to agriculture and mining to be the most volatile. Horvath estimates the parameters of neutral sectoral productivity shocks from the residuals of outputs minus weighted factor inputs using energy usage to correct for variations in capital utilization. In order to compare the two sets of estimates, notice that the standard deviation of the innovation of Horvath's neutral shock in sector j correspond to $\nu^j \sigma_{z^j}$ in our model with labor-augmenting shocks. Figure 2 plots the two sets of estimates, with a "plus" ("circle") denoting cases where the null hypothesis that the true value equals the one estimated by Horvath cannot (can) be rejected at the 5 percent significance level. The hypothesis cannot be rejected for 25 of the 30 sectors in our sample but is rejected for oil and gas extraction, paper, leather, metal mining, and tobacco products. In the latter two cases, the hypothesis would not be rejected at the 1 percent level. Finally, the correlation between both sets of estimates is 0.41 and statistically different from zero.

Overall, results reported so far support the idea that our highly disaggregated DSGE model with heterogenous price rigidity captures reasonably well basic features of the micro data, and motivate the policy analysis carried out below.

4.3 Model with Identical Price Rigidity Across Sectors

We now report parameter estimates for a restricted version of the model where price rigidity is the same in all sectors. Although this restriction (that is, that $\phi^j = \phi$ for all j) is rejected by the data, this model is the appropriate benchmark to evaluate the contribution of modeling heterogeneity in price rigidity. The estimate of the price rigidity parameter is 6.48 (0.92), which implies a duration of 1.58 quarters for prices in all sectors (see Panel B in Table 3). Since the median price rigidity parameter in the heterogeneous model is 4.80 and numerically close to 6.48, we conclude that the differences in the implications of both models arise primarily from the heterogeneity price rigidity in the latter model rather than from quantitative differences in the median price rigidity.

Table 4 reports estimates of the other parameters of the restricted model. They are generally consistent with those obtained for the heterogenous model though, as one would expect, the parameters of the sectoral productivity shocks are more precisely estimated.

5. Implications of Heterogeneity in Price Rigidity

This section shows that modeling the heterogeneity of price rigidity across sectors in the context of a fully-specified macro mode has important implications for understanding the sectoral and aggregate effects of monetary policy.

5.1 Sectoral Effects of Monetary Policy

We study first the effects of a monetary policy shock on sectoral output and inflation by means of impulse-response analysis. In particular, we consider the effects of an innovation that unexpectedly increases the rate of money growth by 1 percent after which, with innovations set to zero, money growth gradually returns to its steady state at the rate ρ_μ.

The responses of sectoral inflation rates in the model with heterogeneous price rigidity are plotted as continuos lines in Figure 3. The horizontal axis are quarters and the vertical axis are percentage deviations from the steady state. This figure shows that all inflation rates increase following the shock but that there is substantial heterogeneity in the size and dynamics of the sectoral responses. Some sectoral inflations react strongly to the shock but return rapidly to their steady state, while others respond weakly and return slowly and monotonically to their steady state. In order to understand this heterogeneity in sectoral inflation responses, we statistically examine the relation between the initial sectoral response (that is, the response in Quarter 1) and several sectoral characteristics using an ordinary least squares (OLS) regression. The sectoral characteristics are price rigidity (measured by the implied durations reported in Table 3), whether the sector produces a capital good or not,[15] labor and materials intensity,[16] the standard deviation of the productivity shock, and the proportion of materials that are purchased from flexible-price producers. For the computation of the latter variable, we classify as flexible-price producers all sectors for which the null hypothesis that $\phi_j = 0$ cannot be rejected (see Table 3). Then, for each sector in our sample, we add up the input shares (from the Use Table) of those flexible-price sectors. The average sector buys around 60 percent of its materials inputs from flexible-price sectors, but the proportion varies greatly across sectors, ranging from 18 percent in apparel to 88 percent in tobacco products.

OLS results are reported in Column 1 of Table 5. Note that the price rigidity coefficient is

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[15] The capital-good producing sectors are construction, lumber and wood, furniture and fixtures, primary metal, fabricated metal, nonelectric machinery, electric machinery, transportation equipment, instruments, miscellaneous manufacturing, and stone, clay and glass.

[16] Since production functions exhibit constant returns to scale, intensities are linearly dependent. For this reason we dropped one of them (capital) from the analysis.

statistically significant at the 5 percent level whereas the other coefficients are not.[17] The negative coefficient of price rigidity means that, as one would expect, sectors with flexible prices (that is, shorter price durations) would tend to increase their prices by more than sectors with rigid prices following an expansionary monetary policy shock. Overall, our analysis suggests that heterogeneity in price rigidity is crucial understand the cross-sectional heterogeneity in sectoral inflation responses to monetary policy shocks.

The coefficient of materials intensity is negative meaning that sectors that require more materials as productive inputs would tend to increase their prices by less after a monetary shock. In an important paper, Basu (1995) theoretically shows that intermediate inputs amplify price rigidity in a roundabout production economy. In particular, when intermediate goods are used in production, the marginal cost rises by less following a monetary policy shock. Hence, prices increase by less and output increases by more, compared with the case without materials. Exploiting the cross-sectional heterogeneity in materials used across sectors, our results provide some support for the empirical importance of this mechanism. The coefficient here is only significant at the 15 percent level (the p-value is 0.14), but output results reported below are more conclusive.

It is interesting to compare these results with those obtained in the benchmark model where price rigidity is the same in all sectors. The responses of sectoral inflation rates to a monetary policy shock in this case are plotted in Figure 3 using dotted lines. Comparing the responses under both models shows that responses in the model with identical rigidity are generally smaller and less variable than in the model with heterogenous rigidity: The initial effect in the former range from 0.7 to 1.5 percentage points while in the latter range from 0.2 to 3.4. The reason is that the model with identical rigidity tends to understate the response by flexible-price sectors and overstate the response by rigid-price sectors. On the other hand, the correlation between both set of responses is high. For example, the correlation between the initial responses in both models is 0.7. These results suggests that other mechanisms common to both models (for example, materials inputs) work in the same direction in both specifications, but that the model with identical price rigidity misses a key source of sectoral heterogeneity, namely price rigidity.

These conclusions are supported by the OLS results reported in Column 3 of Table 5. Except for the coefficient of the standard deviation of the productivity shock, the other coefficients have the same sign in both models. A difference, however, is that for the model with identical rigidity, some coefficients (for example, that of materials intensity) are now statistically significant because, by construction, this model cannot account for the cross-sectional variation in sectoral responses on the

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[17] We computed the correlation matrix of the regressors and found that they range from -0.63 to 0.34. Thus, it is unlikely that these results are driven by collinearity among the explanatory variables.

basis of heterogeneity in price rigidity. Since the common price rigidity is subsumed in the constant term (which is now statistically significant), this model can only account for the cross-sectional variation relative to a sector with typical price rigidity.

We now consider the effects of a monetary policy shock on sectoral outputs in the model with heterogenous price rigidity. The continuos lines in Figure 4 shows that sectoral outputs increase following the monetary policy shock. The only exception is tobacco products whose output initially contracts by 0.07 percent but eventually expands after the third quarter. Thus, in general, there is positive output comovement following a monetary shock. Figure 4 also shows considerable heterogeneity in sectoral output responses. Sectors that react the least are producers of primary goods (agriculture, metal mining, oil and gas extraction) or basic manufactured commodities (tobacco products and chemicals). It is important to note that the sector that responds the most is construction, followed by lumber and wood, primary metal, transportation equipment, stone, clay and glass, and fabricated metal. All these sectors are producers of capital goods and that the latter ones are large inputs to construction: The percentage of materials input expenditures by construction that go into lumber and wood, primary metal, and stone, clay and glass, and fabricated metal are 10.3, 2.8, 8.4, and 12.6 respectively, while the percentage of capital input expenditures that goes into transportation equipment is 33.4. This result is important because 1) it shows that the construction sector plays a prominent role in the transmission of monetary policy, and 2) it illustrates the fact that input-output interactions are crucial to understand how aggregate shocks propagate in actual economies.

The relation between sectoral output responses and sectoral characteristics is reported in Column 2 of Table 5. OLS results indicate that the coefficients attached to whether the sectors produce a capital good and to materials intensity are statistically significant at the 5 percent level, while the other coefficients are not significant. The finding that the coefficient of capital-good production is positive means that sectors that produce capital goods tend to increase their output by more than non-capital good producers after an expansionary monetary policy shock. This result is due to the input-output structure of the economy and, in particular, to the fact that a general increase in output by all sectors requires an increase in the production of capital goods. Since the production of capital goods is concentrated in relatively small sectors, their output response is proportionally larger than that of other sectors. The implication that capital-good producers react strongly to monetary policy shocks is consistent with the VAR evidence reported by Barth and Ramey (2001) and Erceg and Levin (2006).

The finding that the coefficient of materials intensity is positive means that sectors that require more materials inputs would tend to increase their output by more after a monetary shock. As mentioned above this is the mechanism suggested by Basu (1995), and our results provide empirical evidence about its quantitative importance. Notice, however, that this mechanism, albeit still present, becomes statistically insignificant in an economy in which prices in all sectors are equally rigid (see Column 4 in Table 5).

The effects of a monetary policy shock on sectoral outputs in the economy with identical price rigidity are also plotted in Figure 4 using dotted lines. It is interesting to note that for almost all sectors, these responses are smaller than those implied by the model with heterogenous price rigidity. Thus, the real effects of monetary shocks at the sectoral level are larger in a setup that explicitly incorporates the cross-sectional variation in price rigidity which is apparent in the micro data. In turn, we will see below that this has implications for money nonneutrality and the importance of monetary policy at the aggregate level.

5.2 Relative Price Dispersion

Since the equilibrium in this model is symmetric within sectors but asymmetric across sectors, sectoral relative prices are not all equal to 1. To avoid ambiguity, we focus here on the relative price p_t^j/P_t, which is also the real price. The distribution of real prices in steady state (not shown) has a mean of 0.90 and a relatively large standard deviation of 0.28. Since sectoral inflations react differently to a monetary policy shock, it follows that monetary policy shocks induce changes in the distribution of relative prices. This can be seen in Figure 5 which plots the standard deviation of real prices following the monetary shock under the heterogenous price rigidity model (see the continuos line). Notice that starting at the steady state value of 0.28, the standard deviation rises to 0.86 in the quarter following the shock. Hence, there is a large increase in relative price dispersion as a result of the monetary policy shock. This result is primarily due to the strong price response by flexible price producers. Moreover, the effects of monetary policy on relative prices dispersion are long-lived and only after six quarters does the standard deviation approaches its steady state value. This result is important because the welfare effects of these price changes may be potentially large and have substantial implications for the design of monetary policy. For example, in one-sector models, optimal monetary policy involves stabilizing the aggregate price level, but research by Aoki (2001), Huang and Liu (2005), and Erceg and Levin (2006) indicates that this strategy may be sub-optimal in an economy where sectors are characterized by different degrees of nominal rigidity.

In contrast, under the model with identical price rigidity across sectors (see the dotted line), the effect of the monetary policy shock on relative price dispersion is muted and the standard deviation is almost unchanged after the shock.

5.3 Inflation Persistence

The persistence and volatility of aggregate output and inflation predicted by the models with heterogeneous and identical price rigidity are computed by means of simulation and reported in Table 6. Persistence is measured by the sum of autocorrelation coefficients selected using the Modified Information Criterion (MIC) and volatility is measured by the unconditional standard deviation of the simulated series.

For the heterogeneous rigidity model, aggregate inflation persistence is 0.51, which is much larger than that of the median sector (0.21) and relatively close to that found in U.S. data (0.71). In contrast, for the model with identical price rigidity across sectors, aggregate inflation persistence is equal to that of the median sector, which is only 0.25. This result suggests that sectoral heterogeneity in price stickiness substantially increases the predicted persistence of aggregate inflation. This is important because existing models based on forward-looking pricing rules usually predict lower inflation persistence than in the data and, as a strategy to address this shortcoming, assume an indexation mechanism whereby rule-of-thumb firms fix their prices as a function of past inflation (see, among others, Gali and Gertler, 1999, and Christiano, Eichenbaum and Evans, 2005). Instead, in our model, inflation persistence arises from the aggregation of sectoral inflation rates with different degrees of persistence.[18] This mechanism is attractive and plausible because indeed statistical agencies estimate inflation by aggregating prices into a CPI using expenditure weights and then computing its percentage change, just as is done in this model.

Regarding output persistence, estimates are similar in both models and quite close to that in U.S. data. Table 6 also shows that aggregate variables are considerably less volatile than the median sector in both models. While inflation volatility is quantitatively close that of U.S. CPI inflation, especially for the heterogeneous rigidity model, both models tend to overpredict output volatility.

5.4 Monetary Policy and Aggregate Fluctuations

Table 7 reports the contribution of different shocks to the unconditional variance of aggregate output and inflation. Two important conclusions emerge from this table. First, the model with identical price rigidity attributes a large share to sectoral productivity shocks in accounting for the variance of aggregate output (90 percent) and inflation (12 percent). Instead, the model with heterogenous price rigidity suggests a modest role to sectoral shocks in explaining aggregate variables and, in particular, attributes most of the variance of aggregate output to the (aggregate) labor supply shock (64 percent). Previous papers that study the relative importance of aggregate versus sectoral

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[18] The role of aggregation in explaining the observed persistence of CPI inflation is also examined by Clark (2006) and Altissimo, Mojon, and Zaffaroni (2007).

shocks in the context of real business cycle models include Long and Plosser (1987), Dupor (1999) and Horvath (2000). Our results, based on a monetary model, tend to support the view that sectoral shocks make a limited contribution to business cycle fluctuations (see, for example, Dupor, 1999).

Second, the model with identical price rigidity indicates that monetary policy shocks account for only 5 percent of the variance of output, but this proportion rises to 24 percent in the model with heterogenous price rigidity. The latter fraction is in line with the estimate reported by Shapiro and Watson (1988), who find that nominal shocks account for 28 percent of output variations. This result reflects the role of heterogeneity in price rigidity in amplifying the degree of aggregate money non-neutrality, a feature that is also discussed by Carvalho (2006) and Nakamura and Steinsson (2010) in the context of more restricted models. In turn, this suggests that ignoring the cross-sectional variation in price rigidity can lead to a substantial mis-measurement of the contribution of monetary policy to aggregate fluctuations.

6. The Importance of Sectoral Productivity Shocks

The results in the previous section indicate that sectoral shocks play a limited role in explaining the unconditional variance of aggregate variables. However, we will see in this section that sectoral shocks are crucial to understand the behavior of the micro data and, in particular, that sectoral shocks are an important contributors to the persistence and volatility of sectoral output and inflation and account for a significant part of the unconditional variance of sectoral variables.

6.1 Sectoral Persistence and Volatility

The persistence and volatility of sectoral outputs and inflation rates are reported in Table 8. From this table, it is clear that there is limited heterogeneity in sectoral output persistence. The distribution only ranges from 0.83 in lumber and wood to 0.97 in tobacco products, is negatively skewed, and has a relatively high median of 0.93. In contrast, there is large heterogeneity in sectoral inflation persistence, ranging from -0.16 in FIRE to 0.90 in apparel. The distribution (not shown) is bimodal as a result of the mixture of one distribution for flexible-price sectors and another one for rigid-price sectors. Finally, inflation persistence in the median sector is 0.21, which as we saw above, is much less than the persistence of aggregate inflation (0.51).

We examine the relation between sectoral persistence and volatility, and sectoral characteristics using OLS regressions and report results in Table 9. In the regression where the persistence of sectoral inflation is the dependent variable, the only statistically significant coefficient is that of price rigidity. Thus, sectors with more rigid prices (that is, longer price durations) tend to have more persistent inflation rates. In contrast, when the dependent variable is the persistence of sectoral output, the only statistically significant coefficient is whether the sector produces a capital good or not. Since the coefficient is negative, the output of capital-good producers is generally less persistent than that of other sectors.

Regarding volatility, Table 8 shows heterogeneity in both sectoral outputs and inflation rates with both distributions mildly positively skewed. The regressions in Table 12 indicate that price rigidity and whether the sector produces a capital good are respectively important to understand the cross-sectional variation in inflation and output volatilities. However, the standard deviation of the sector-specific productivity shocks is also important to account for the heterogeneity in sectoral outputs and inflation rates. These results strongly suggest the importance of sectoral shocks on the volatility of sectoral variables and motivate the more detailed quantitative analysis that follows.

6.2 Variance Decomposition

Figure 6 reports the proportion of the unconditional variance of sectoral inflation, marginal cost, real price, and gross output that is accounted for by each of the shocks. In order to reduce cluttering, we focus on the productivity shock to its own sector, the three aggregate shocks, and two sectoral productivity shocks (those to agriculture and oil production) which have substantial effects on other sectors.

First, consider the sectoral inflations in Panel A. Except for agriculture and most mining sectors, monetary policy shocks account for most of the variance of sectoral inflations, ranging from 45 percent in printing and publishing to 82 percent in wholesale and retail trade. This result is consistent with the finding above that monetary policy explains 72 percent of the variance of aggregate inflation (see Table 7). The productivity shock to its own sector accounts for most of the inflation variance in agriculture and most mining sectors, and plays a fairly large role in the other sectors as well, especially in manufacturing. The money demand shock is also quantitatively important, especially in services where it accounts for 30 percent of the inflation variance in finance, insurance and real estate. In contrast, the labor supply shocks plays a very limited role in accounting for the variance of sectoral inflation, except for wholesale and retail trade, which is the most labor-intensive sector in the U.S. economy and where it accounts for 10 percent of the inflation variance.

In summary, although monetary shocks (monetary policy and money demand) jointly account for most of the variance in sectoral inflations, the idiosyncratic shock is quantitatively important and generally plays a larger role is explaining sectoral inflation compared with aggregate inflation. Statistical factor models like those used by Boivin, Giannoni, and Mihov (2007), and Mackowiak, Moench, and Wiederholt (2009) also find that sector-specific conditions are important determinants of sectoral inflation rates. However, it is important to note that in factors models the idiosyncratic shock is basically a residual while in this model it is a structural disturbance. Moreover, the economic structure of this model means that idiosyncratic sectoral shocks may have quantitatively important effects in other sectors as a result of input-output interactions. For example, Panel in Figure 6 shows that productivity shock to agriculture accounts for 25, 9 and 4 percent of the inflation variance in food products, tobacco products, and lumber and wood, respectively. This result is, of course, due to the fact that agricultural goods are a major input to these sectors, representing 38, 22, and 13 percent of their materials expenditures, respectively.

Second, consider the sectoral marginal costs in Panel B. Although there is considerable heterogeneity across sectors, the productivity shock to its own sector accounts for most of the variance in the marginal cost in most sectors. Exceptions are services, construction, food products, tobacco products, and oil refining. In the case of services and construction, monetary policy is particularly important in accounting for the variance of the marginal cost. In the case of food and tobacco products, the productivity shock to agriculture accounts for 61 and 14 percent, respectively, of the variance of the marginal cost. Finally, in the case of oil refining, the productivity shock to oil production accounts for 14 percent of the variance of the marginal cost. The latter two results underscore the importance of modeling sectoral interactions in order to understand the behavior of sectoral variables and the role of commodity shocks in inter-sectoral reallocations.

Third, consider the sectoral real prices in Panel C. Except for services, the unconditional variance of real prices is mostly accounted for the productivity shock to its own sector. For services, the variance in the real price is primarily accounted for by the monetary policy shock. Again, we see in Panel C that input-output interactions induce the productivity shock in one sector to have substantial effects other ones. Quantitatively, this is especially important in the case of productivity shocks to agriculture and oil production: The productivity shock to agriculture accounts for a significant proportion of the variance of the real price in food products (52 percent), tobacco products (14 percent), transport and utilities (32 percent), and trade (16 percent), while the productivity shock to oil production accounts for 15 percent of the variance of the real price in oil refining. Overall, these results suggest that sectoral shocks are an important cause of the price changes observed at the micro level and explain the empirical observation (see Klenow and Kryvtsov, 2008) that average price changes, measured by the percentage change in the CPI, are very small compared with individual price changes.

Finally, consider the sectoral outputs in Panel D. There is considerable heterogeneity across sector concerning the relative importance of the various shocks in accounting for the unconditional variance of output. Overall, the most important aggregate shock is the labor supply shock, but the monetary policy shock is quantitatively important for construction and primary metal, which is large a input to construction. As before, the role of productivity shock to its own sector is substantial, as it is the shock to agriculture in the case of food and tobacco products.

7. Conclusions

This paper constructs and estimates a highly disaggregated, multi-sector DSGE model where sectors are heterogenous in production functions, price rigidity and the combination of materials and investment inputs employed in their production processes. These features are prominent in the data and, as we show, are crucial to understand the dynamics of aggregate and sectoral variables following a monetary policy shock. Relaxing the assumption of symmetry in standard models, allows us to explore the effects of aggregate and sectoral shocks at both the aggregate and sectoral levels. This, combined with the very disaggregated nature of our analysis means that we can successfully bridge two large strands of the literature in Macroeconomics: the one based on DSGE models and the one that directly studies the statistical properties of the micro data. Our multi-sector setup allows us to get as close as one possibly can to the micro data, while preserving the theoretical advantages of the fully-specified DSGE framework.

Table 1. Sectors and Production Functions

	SIC	ν^j		α^j		γ^j	
Sector	Codes	Estimate	s.e	Estimate	s.e	Estimate	s.e
Agriculture	1 − 9	0.261*	0.006	0.142*	0.005	0.597*	0.006
Metal Mining	10	0.328*	0.011	0.306*	0.015	0.366*	0.024
Coal Mining	12	0.432*	0.009	0.194*	0.008	0.374*	0.010
Oil and Gas Extraction	13	0.176*	0.004	0.456*	0.009	0.368*	0.011
Nonmetallic Mining	14	0.314*	0.004	0.254*	0.006	0.432*	0.009
Construction	15 − 17	0.394*	0.004	0.052*	0.001	0.554*	0.005
Food Products	20	0.161*	0.002	0.084*	0.005	0.755*	0.006
Tobacco Products	21	0.146*	0.005	0.290*	0.018	0.564*	0.021
Textile Mill Products	22	0.229*	0.004	0.067*	0.002	0.704*	0.005
Apparel	23	0.325*	0.005	0.060*	0.003	0.615*	0.007
Lumber and Wood	24	0.247*	0.004	0.100*	0.003	0.653*	0.003
Furniture and Fixtures	25	0.365*	0.003	0.079*	0.002	0.557*	0.003
Paper	26	0.261*	0.002	0.136*	0.003	0.603*	0.003
Printing and Publishing	27	0.398*	0.004	0.124*	0.003	0.478*	0.006
Chemicals	28	0.237*	0.003	0.183*	0.004	0.581*	0.006
Oil Refining	29	0.091*	0.005	0.103*	0.004	0.806*	0.008
Rubber and Plastics	30	0.323*	0.002	0.091*	0.002	0.586*	0.002
Leather	31	0.326*	0.005	0.089*	0.007	0.585*	0.003
Stone, Clay and Glass	32	0.369*	0.004	0.125*	0.004	0.507*	0.002
Primary Metal	33	0.229*	0.003	0.084*	0.002	0.687*	0.004
Fabricated Metal	34	0.346*	0.002	0.104*	0.003	0.549*	0.003
Nonelectric Machinery	35	0.361*	0.004	0.112*	0.002	0.527*	0.003
Electric Machinery	36	0.350*	0.005	0.127*	0.006	0.523*	0.003
Transportation Equip.	37	0.283*	0.004	0.080*	0.004	0.637*	0.003
Instruments	38	0.460*	0.006	0.100*	0.003	0.440*	0.005
Misc. Manufacturing	39	0.327*	0.005	0.117*	0.007	0.555*	0.006
Transport and Utilities	40 − 49	0.314*	0.005	0.248*	0.004	0.437*	0.009
Trade	50 − 59	0.500*	0.005	0.148*	0.002	0.352*	0.007
FIRE	60 − 67	0.283*	0.004	0.356*	0.006	0.361*	0.005
Other Services	70 − 87	0.427*	0.002	0.195*	0.005	0.378*	0.006

Note: FIRE stands for finance, insurance and real estate. s.e. denotes standard error and $*$ denotes significance at the 5 percent level.

Table 2. Correlation between Commodity-Based and Industry-Level Inflation

Sector	Correlation
Agriculture	*n.a.*
Coal Mining	0.940*
Oil and Gas Extraction	0.586*
Nonmetallic Mining	0.687*
Food Products	0.857*
Tobacco Products	0.998*
Lumber and Wood	0.981*
Furniture and Fixtures	0.753*
Paper	0.964*
Chemicals	0.923*
Oil Refining	0.998*
Rubber and Plastics	0.963*
Leather	0.646*
Stone, Clay and Glass	0.881*

Notes: $*$ denotes significance at the 5 percent level. The statistic used to test the null hypothesis that the correlation is zero is computed as $R\sqrt{T-2}/\sqrt{1-R}$ where R is the correlation coefficient and T is the sample size. Under the null, this statistic follows a t distribution with $T-2$ degrees of freedom (see Hogg and Craig, 1978, pp. 300-301). The sample period used to compute these correlations is 1986Q2 to 2002Q4 for coal, oil and natural gas, and oil refining, and 1985Q2 to 2002Q4 for the other sectors. We were unable to compute the correlation for agriculture because no industry-level PPI is produced for this sector by the BLS.

Table 3. Sectoral Price Rigidities

					Duration in Micro Data			
	ϕ^j					NS		BK
			Implied	Implied		CPI	CPI	CPI
Sector	Estimate	s.e.	Probability	Duration	PPI	Regular	Final	Final
	A. Heterogeneous Price Rigidity							
Agriculture	0.001	2.10	0.000	1.00	0.38	1.91	1.32	1.20
Metal Mining	4.81	7.46	0.319	1.47				
Coal Mining	2.80	5.80	0.235	1.31				
Oil and Gas Extraction	0.056	7.07	0.008	1.01				
Nonmetallic Mining	81.42*	9.51	0.748	3.96				
Construction	140.7*	7.69	0.802	5.04				
Food Products	189.9*	7.96	0.827	4.77	1.25	3.21	1.55	1.11
Tobacco Products	0.001	1.81	0.000	1.00		1.34	0.88	1.40
Textile Mill Products	13.78*	5.48	0.498	1.99				
Apparel	666.7*	7.90	0.904	10.41	9.01	10.18	0.87	0.91
Lumber and Wood	70.88*	4.90	0.732	3.73	7.58			
Furniture and Fixtures	158.3*	12.09	0.812	5.31	5.85	6.29	1.35	1.29
Paper	1.46	1.97	0.151	1.18	3.55			
Printing and Publishing	24.72*	8.21	0.592	2.45		6.55	4.94	5.39
Chemicals	0.199	0.95	0.027	1.02	2.95	4.25	2.23	2.08
Oil Refining	1.80	8.23	0.175	1.21	0.68	0.26	0.24	0.20
Rubber and Plastics	4.79	2.76	0.318	1.47	8.33			
Leather	330.7*	5.04	0.866	7.46	5.21	9.62	1.12	1.13
Stone, Clay and Glass	21.33	14.01	0.569	2.32	5.46			
Primary Metal	507.5*	16.94	0.890	9.13				
Fabricated Metal	0.009	1.62	0.001	1.00				
Nonelectric Machinery	0.001	3.00	0.000	1.00		5.45	1.98	1.31
Electric Machinery	0.005	5.69	0.001	1.00		4.59	1.59	1.35
Transportation Equip.	42.75*	14.56	0.670	2.03	0.74	3.02	2.61	0.80
Instruments	0.001	12.80	0.000	1.00		6.05	2.03	3.11
Misc. Manufacturing	4.29	4.08	0.301	1.43	2.02	9.14	2.43	1.76
Transport and Utilities	151.1*	13.30	0.808	5.20		1.67	1.66	2.11
Trade	423.8*	10.73	0.881	8.38		6.70	6.40	3.65
FIRE	0.004	1.92	0.000	1.00				2.00
Other Services	0.305	1.71	0.040	1.04		5.81	5.63	4.10
	B. Identical Price Rigidity							
All Sectors	6.48*	0.92	0.631	1.58				

Note: $*$ denotes significance at the 5 percent level.

Table 4. Other Parameter Estimates

	Heterogenous Rigidity		Identical Rigidity	
Description	Estimate	s.e	Estimate	s.e.
Capital adjustment parameter	4.710	3.804	2.800	2.424
AR coefficient of productivity shock				
Agriculture	0.922	0.743	0.412*	0.208
All mining sectors	0.827*	0.317	0.997*	0.320
Construction	0.852	12.05	0.778*	0.196
All manufacturing sectors	0.949*	0.210	0.998*	0.047
All service sectors	0.763	4.200	0.999*	0.026
SD of productivity innovation				
Agriculture	0.111*	0.018	0.232*	0.031
All mining sectors	0.063	0.049	0.024*	0.008
Construction	0.024	0.692	0.177	0.112
All manufacturing sectors	0.033	0.031	0.019	0.013
All service sectors	0.020	0.058	0.003	0.045
AR coefficient of labor supply shock	0.984*	0.092	0.999*	0.097
SD of labor supply innovation	0.012	0.018	0.001	0.040
AR coefficient of money demand shock	0.711*	0.146	0.271	0.353
SD of money demand innovation	0.186*	0.066	0.226*	0.040
AR coefficient of monetary policy shock	0.456*	0.068	0.267*	0.076
SD of monetary policy innovation	0.008*	0.001	0.008*	0.001

Note: $*$ denotes significance at the 5 percent level.

Table 5. Relation Between Sectoral Responses and Sectoral Characteristics

Sectoral Characteristic	Heterogenous Rigidity: Sectoral Inflation	Heterogenous Rigidity: Sectoral Output	Identical Rigidity: Sectoral Inflation	Identical Rigidity: Sectoral Output
Intercept	2.940	−0.306	2.118*	1.153
	(1.447)	(2.131)	(0.272)	(0.733)
Price rigidity	−0.221*	0.063	–	–
	(0.053)	(0.076)		
Capital-good producer	0.098	1.322*	0.179*	1.068*
	(0.253)	(0.436)	(0.043)	(0.226)
Labor intensity	−0.940	4.316	−1.005*	0.619
	(1.620)	(2.218)	(0.384)	(1.181)
Materials intensity	−1.879	3.939*	−1.488*	0.239
	(1.236)	(1.581)	(0.273)	(0.802)
Flexible-price inputs	0.814	−0.990	–	–
	(0.693)	(1.497)		
SD of productivity shock	1.029	−7.412	−0.837	−2.403
	(2.815)	(4.650)	(0.639)	(2.109)
R-squared	0.707	0.654	0.644	0.591

Notes: ∗ denotes significance at the 5 percent level. White heteroskedasticity-consistent standard errors are reported in parenthesis.

Table 6. Aggregate Persistence and Volatility

	Persistence		Volatility	
	Aggregate Inflation	Aggregate Output	Aggregate Inflation	Aggregate Output
	A. Heterogeneous Rigidity			
Aggregate	0.51	0.95	0.77	4.62
Median Sector	0.21	0.93	1.65	5.46
	B. Identical Rigidity			
Aggregate	0.25	0.95	0.85	4.04
Median Sector	0.25	0.98	1.03	7.49
	C. U.S. Data			
Aggregate	0.71	0.94	0.78	3.20

Table 7. Variance Decomposition

	Heterogeneous Rigidity		Identical Rigidity	
Shock	Aggregate Inflation	Aggregate Output	Aggregate Inflation	Aggregate Output
All Productivity	5.19	5.73	12.14	90.35
Labor Supply	6.70	64.31	0.04	3.01
Money Demand	16.20	6.18	9.57	1.97
Monetary Policy	71.91	23.78	78.25	4.67

Table 8. Sectoral Persistence and Volatility

Sector	Persistence		Volatility	
	Sectoral Inflation	Sectoral Output	Sectoral Inflation	Sectoral Output
Agriculture	−0.06	0.94	4.60	10.16
Metal Mining	0.13	0.93	2.24	5.08
Coal Mining	0.08	0.93	3.05	6.45
Oil and Gas Extraction	−0.10	0.95	2.51	4.13
Nonmetallic Mining	0.59	0.92	0.85	4.79
Construction	0.70	0.84	0.61	9.66
Food Products	0.79	0.95	0.54	5.12
Tobacco Products	−0.08	0.97	2.02	3.77
Textile Mill Products	0.49	0.92	1.14	5.35
Apparel	0.90	0.95	0.40	5.05
Lumber and Wood	0.66	0.83	0.79	7.55
Furniture and Fixtures	0.78	0.91	0.60	5.43
Paper	0.07	0.94	1.77	4.88
Printing and Publishing	0.48	0.94	1.20	6.39
Chemicals	−0.08	0.96	2.36	5.05
Oil Refining	0.09	0.95	1.73	3.54
Rubber and Plastics	0.20	0.92	1.75	5.64
Leather	0.86	0.95	0.46	5.62
Stone, Clay and Glass	0.42	0.88	1.26	6.70
Primary Metal	0.89	0.88	0.36	8.12
Fabricated Metal	−0.11	0.94	2.39	7.26
Nonelectric Machinery	−0.11	0.93	2.59	7.83
Electric Machinery	−0.09	0.95	2.79	7.10
Transportation Equip.	0.58	0.90	0.87	7.01
Instruments	−0.09	0.91	2.95	6.76
Misc. Manufacturing	0.22	0.93	1.58	5.49
Transport and Utilities	0.73	0.93	0.58	4.96
Trade	0.84	0.94	0.43	5.30
FIRE	−0.16	0.96	3.55	4.38
Other Services	−0.09	0.93	3.22	5.02

Table 9. Understanding Sectoral Persistence and Volatility

Sectoral Characteristic	Persistence Sectoral Inflation	 Sectoral Output	Volatility Sectoral Inflation	 Sectoral Output
Intercept	−0.093	0.940*	1.928	−0.698
	(0.371)	(0.068)	(1.758)	(2.699)
Price rigidity	0.100*	−0.001	−0.213*	0.085
	(0.019)	(0.002)	(0.059)	(0.094)
Capital-good producer	−0.026	−0.035*	−0.106	1.530*
	(0.082)	(0.013)	(0.279)	(0.520)
Labor intensity	0.333	−0.027	0.779	7.489*
	(0.396)	(0.062)	(2.081)	(2.498)
Materials intensity	0.550	−0.017	−2.434	2.176
	(0.312)	(0.048)	(1.561)	(2.097)
Flexible-price inputs	−0.358	0.024	1.052	0.899
	(0.276)	(0.049)	(0.687)	(1.687)
SD of productivity shock	0.741	0.052	9.183*	18.364*
	(0.542)	(0.090)	(4.267)	(7.674)
R-squared	0.831	0.435	0.741	0.630

Notes: $*$ denotes significance at the 5 percent level. White heteroskedasticity-consistent standard errors are reported in parenthesis.

A Aggregation

Since net private bond holdings are zero, total share holdings in sector j add up to one, and firms in the same sector are identical, meaning that $p_t^j = p_t^{lj}$, $c_t^j = c_t^{lj}$, $n_t^j = n_t^{lj}$ and $d_t^j = d_t^{lj}$. Then, the aggregate equivalent of the consumer's budget constraint is

$$\sum_{j=1}^{J} \frac{p_t^j c_t^j}{P_t} + m_t = \sum_{j=1}^{J} \frac{w_t^j n_t^j}{P_t} + \sum_{j=1}^{J} \frac{d_t^j}{P_t} + \frac{m_{t-1}}{\pi_t} + \frac{\Upsilon_t}{P_t}. \tag{A1}$$

Substituting in the government budget constraint (19) and multiplying through by the price level yield

$$\sum_{j=1}^{J} p_t^j c_t^j = \sum_{j=1}^{J} w_t^j n_t^j + \sum_{j=1}^{J} d_t^j. \tag{A2}$$

Define the value of gross output produced by sector j

$$V_t^j \equiv p_t^j \left(c_t^j + \sum_{i=1}^{J} x_{j,t}^i + \sum_{i=1}^{J} h_{j,t}^i \right), \tag{A3}$$

and the sum of all adjustment costs in sector j

$$A_t^j = \Gamma_t^j Q_t^{Xj} + \Phi_t^j p_t^j \left(c_t^j + \sum_{i=1}^{J} x_{j,t}^i + \sum_{i=1}^{J} h_{j,t}^i \right). \tag{A4}$$

Then, aggregate nominal dividends are

$$\sum_{j=1}^{J} d_t^j = \sum_{j=1}^{J} V_t^j - \sum_{j=1}^{J} w_t^j n_t^j - \sum_{j=1}^{J} Q_t^{Xj} X_t^j - \sum_{j=1}^{J} Q_t^{Hj} H_t^j - \sum_{j=1}^{J} A_t^j, \tag{A5}$$

where we have used $\sum_{i=1}^{J} p_t^i x_{i,t}^j = Q_t^{Xj} X_t^j$ and $\sum_{i=1}^{J} p_t^i h_{i,t}^j = Q_t^{Hj} H_t^j$. The nominal value added in sector j is denoted by Y_t^j and is defined as the value of gross output produced by that sector minus the cost of materials inputs

$$Y_t^j = V_t^j - Q_t^{Hj} H_t^j. \tag{A6}$$

Substituting (A5) and (A6) into (A2), using $\sum_{j=1}^{J} p_t^j c_t^j = P_t C_t$, and rearranging yield

$$\sum_{j=1}^{J} Y_t^j = P_t C_t + \sum_{j=1}^{J} Q_t^{Xj} X_t^j + \sum_{j=1}^{J} A_t^j. \tag{A7}$$

B Estimation of Production Function Parameters

The production function parameters were estimated using the yearly data on nominal expenditures on capital, labor and materials inputs by each sector collected by Dale Jorgenson for the period 1958 to 1996. Jorgenson records separately expenditures on materials and energy inputs. In order to be consistent with the model, where energy is indistinguishable from other materials inputs, we add these two series into a single expenditure category.

The nominal expenditures predicted by the model may be obtained from the first-order conditions of the firm's problem

$$\nu^j \left(\psi_t^j P_t y_t^j\right) = w_t^j n_t^j, \tag{B1}$$

$$\gamma^j \left(\psi_t^j P_t y_t^j\right) = \sum_{i=1}^{J} p_t^i h_{i,t}^j, \tag{B2}$$

$$\alpha^j \left(\psi_t^j P_t y_t^j\right) = \left(\left(\frac{\Lambda_{t-1}}{\beta \Lambda_t}\right) \Omega_{t-1}^j - (1-\delta)\Omega_t^j\right) P_t k_t^j + Q_t^{X^j} k_t^j \left(\frac{\partial \Gamma_t}{\partial k_t^j}\right), \tag{B3}$$

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 superscripts are dropped. The right-hand sides of these equations are, respectively, the wage bill, total expenditures on materials 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, but the mapping for capital is imperfect because the data do not include adjustment costs and take into account distortionary taxes, from which our model abstracts (see Jorgenson and Stiroh, 2000, Appendix B). In deriving equation (B3) from the first-order condition for k_{t+1}^j, we used the assumption of rational expectations. Hence, this equation holds up to a mean-zero forecast error. 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.

Although the data set does not contain observations on $\psi_t^j P_t y_t^j$, it is possible to construct estimates of α^j, ν^j, and γ^j as follows. Use two of the three ratios: (B1)/(B2), (B1)/(B3) and (B2)/(B3), and the condition $\nu^j + \alpha^j + \gamma^j = 1$ to obtain a system of three equations with three unknowns. The unique solution of this system delivers an observation of the production function parameters for a given year. Our estimates of ν^j, α^j and γ^j are the sample averages of these yearly observations and their standard deviations are $\sqrt{\sigma^2/T}$ where σ^2 is the variance of the yearly observations and $T = 39$ is the sample size.

C Observational Equivalence of the Rotemberg and Calvo Models

The log-linearized sectoral Phillips curve for a generic sector j in our model with quadratic adjustment costs is

$$E_t \hat{\pi}^j_{t+1} = \frac{1}{\beta} \hat{\pi}^j_t - \frac{\theta - 1}{\beta \phi^j} \left(\hat{\psi}^j_t - \hat{\mathsf{p}}^j_t \right),$$

where $\mathsf{p}^j_t = p^j_t / P_t$ is the real price and the circumflex denotes deviation from steady state. The log-linearized sectoral Phillips curve that would be obtained in a version of the model where firms follow Calvo pricing is

$$E_t \hat{\pi}^j_{t+1} = \frac{1}{\beta} \hat{\pi}^j_t - \frac{\left(1 - \varrho^j\right)\left(1 - \beta \varrho^j\right)}{\beta \varrho^j} \left(\hat{\psi}^j_t - \hat{\mathsf{p}}^j_t \right),$$

where ϱ^j is the probability of not changing prices. Notice that the two curves are isomorphic and, given the elasticity of substitution (θ) and the discount rate (β), imply a correspondence between the rigidity parameter ϕ^j in the quadratic cost function and the Calvo probability, ϱ^j. In particular, given $\phi^j > 0$, the sectoral Calvo probability is the smaller root that solves

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

This is a quadratic equation with roots

$$\frac{(\theta - 1) + \phi^j (1 + \beta) \pm \sqrt{\left((1 - \theta) - \phi^j (1 + \beta)\right)^2 - 4\beta \left(\phi^j\right)^2}}{2\beta \phi^j}.$$

Since $\left((1 - \theta) - \phi^j (1 + \beta)\right)^2 - 4\beta \left(\phi^j\right)^2 > 0$ and $(\theta - 1) + \phi^j (1 + \beta) > 0$, it follows that both roots are real and positive. It easy to see that one root is larger than 1 and the other one is less than 1.

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Figure 1: Comparison with Micro Estimates of Price Durations

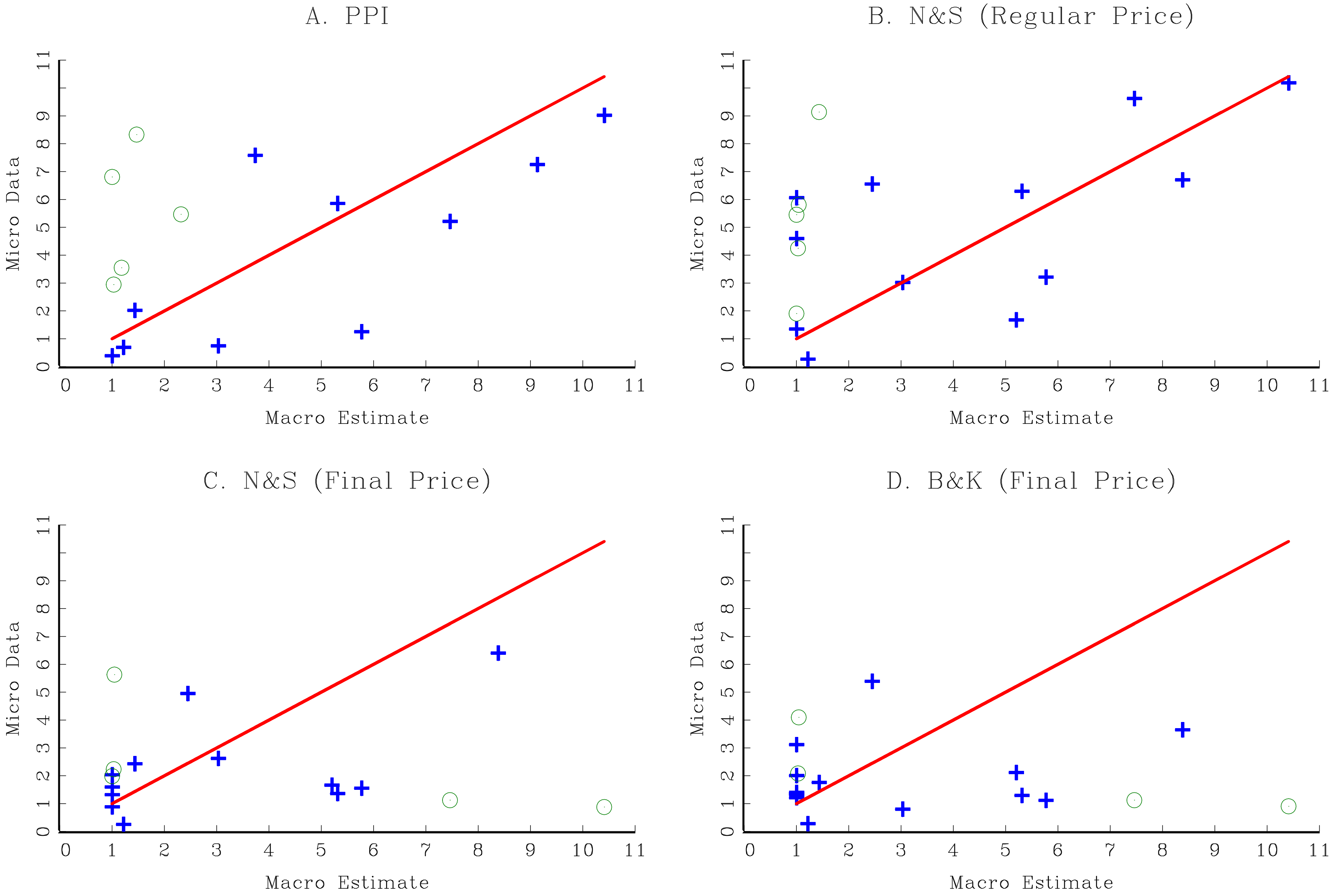


Figure 2: Comparison with Estimates Based on Solow Residuals

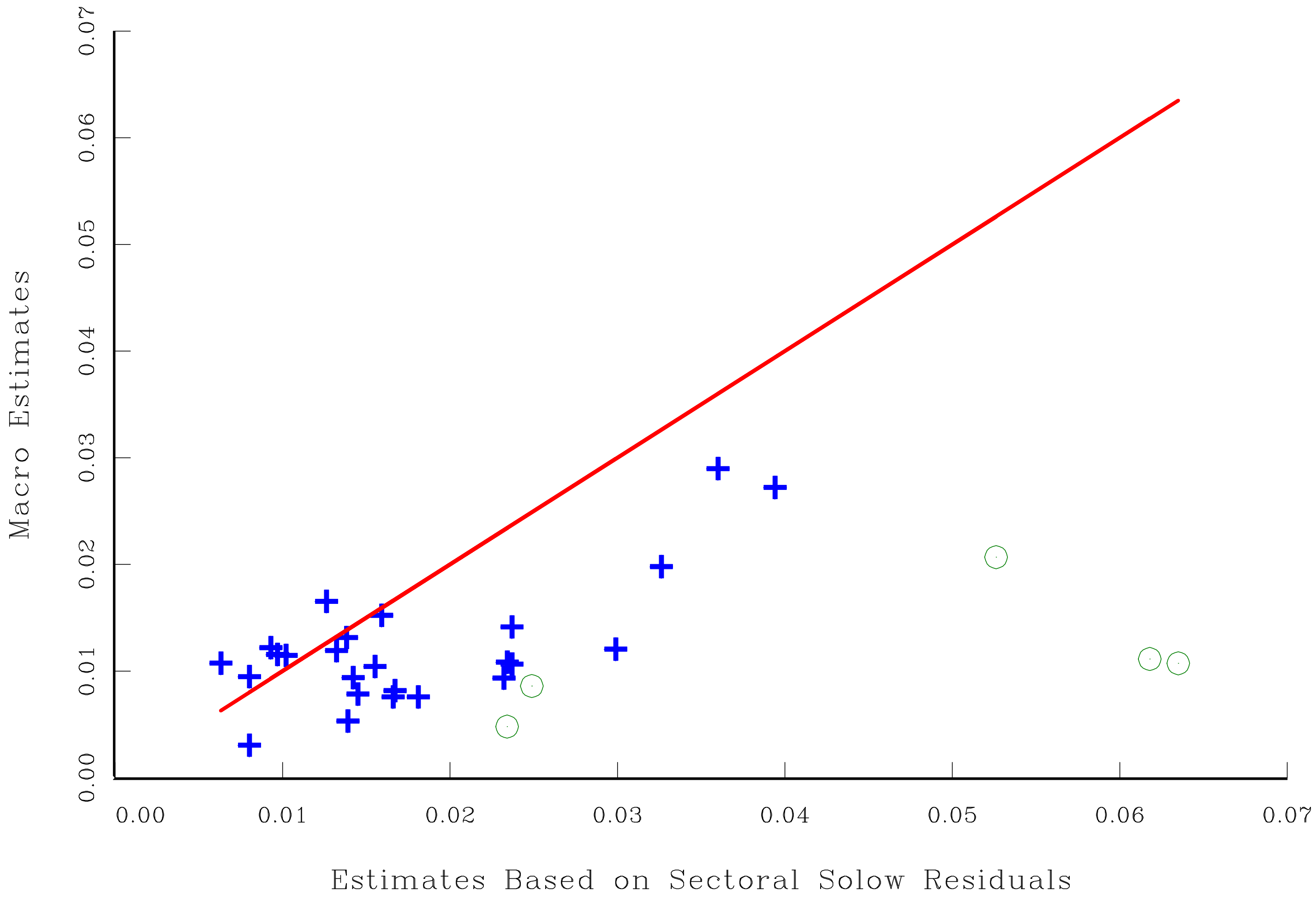


Figure 3: Sectoral Inflation Responses to a Monetary Policy Shock

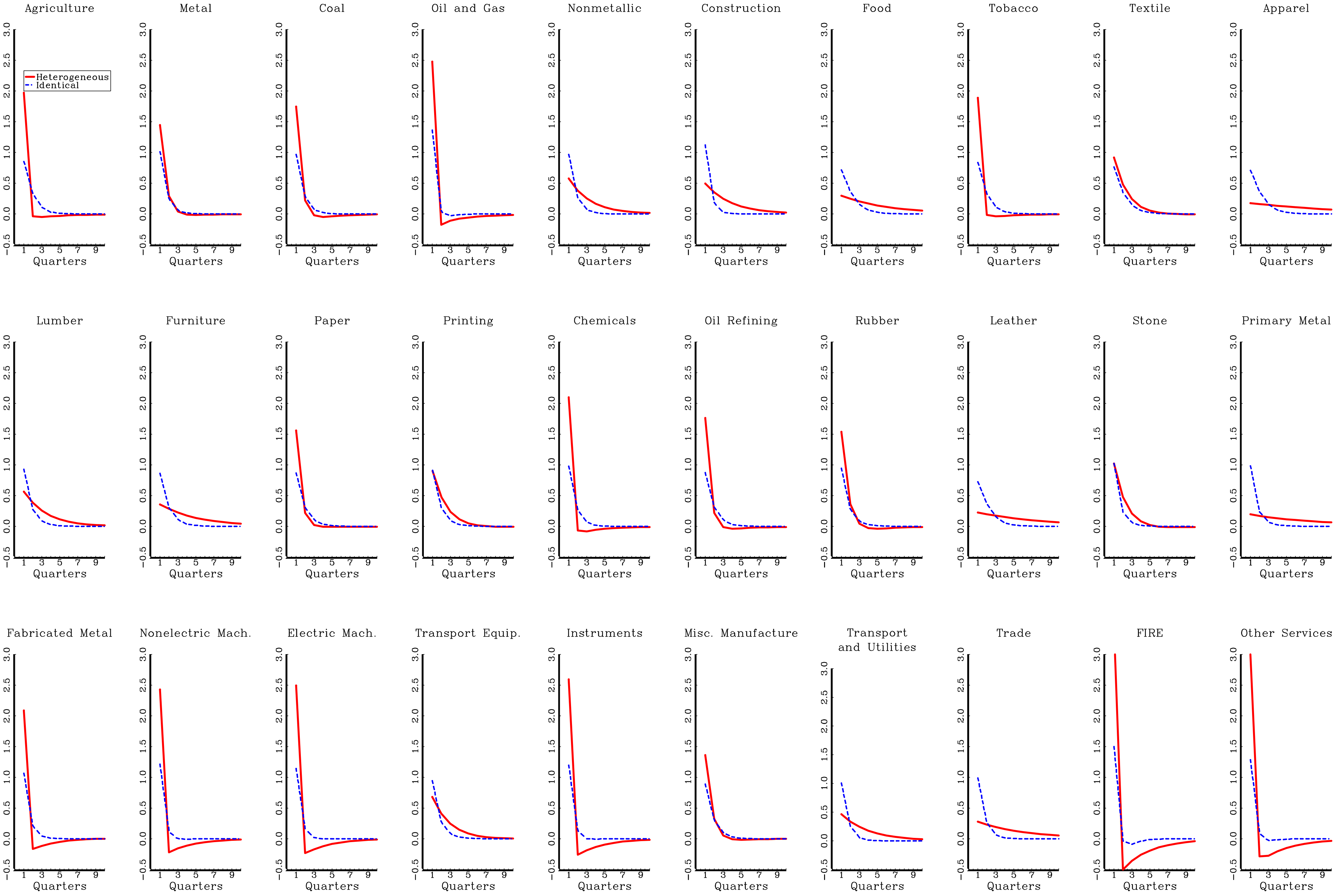


Figure 4: Sectoral Output Responses to a Monetary Policy Shock

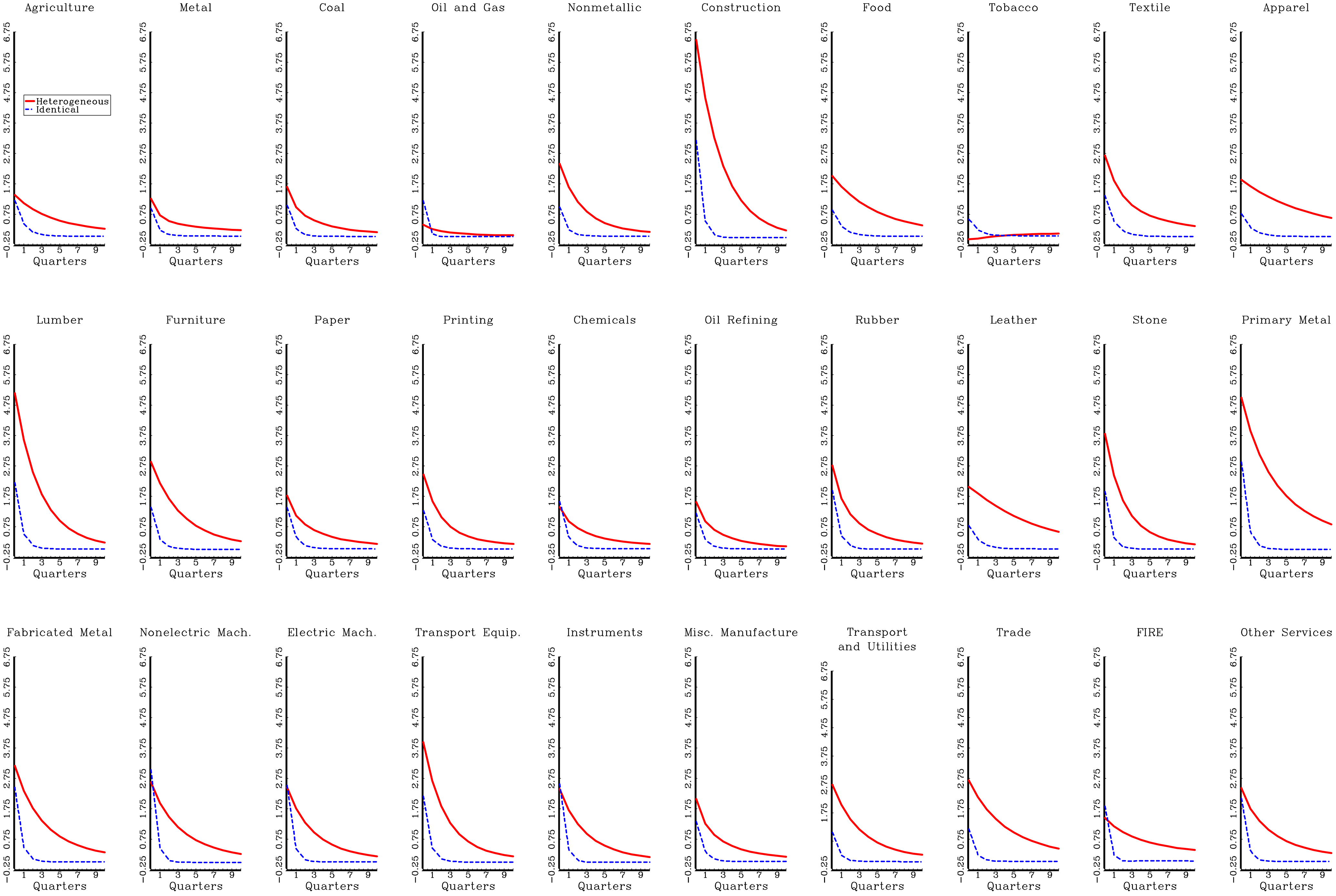


Figure 5: Changes in the Distribution of Real Prices After a Monetary Policy Shocks

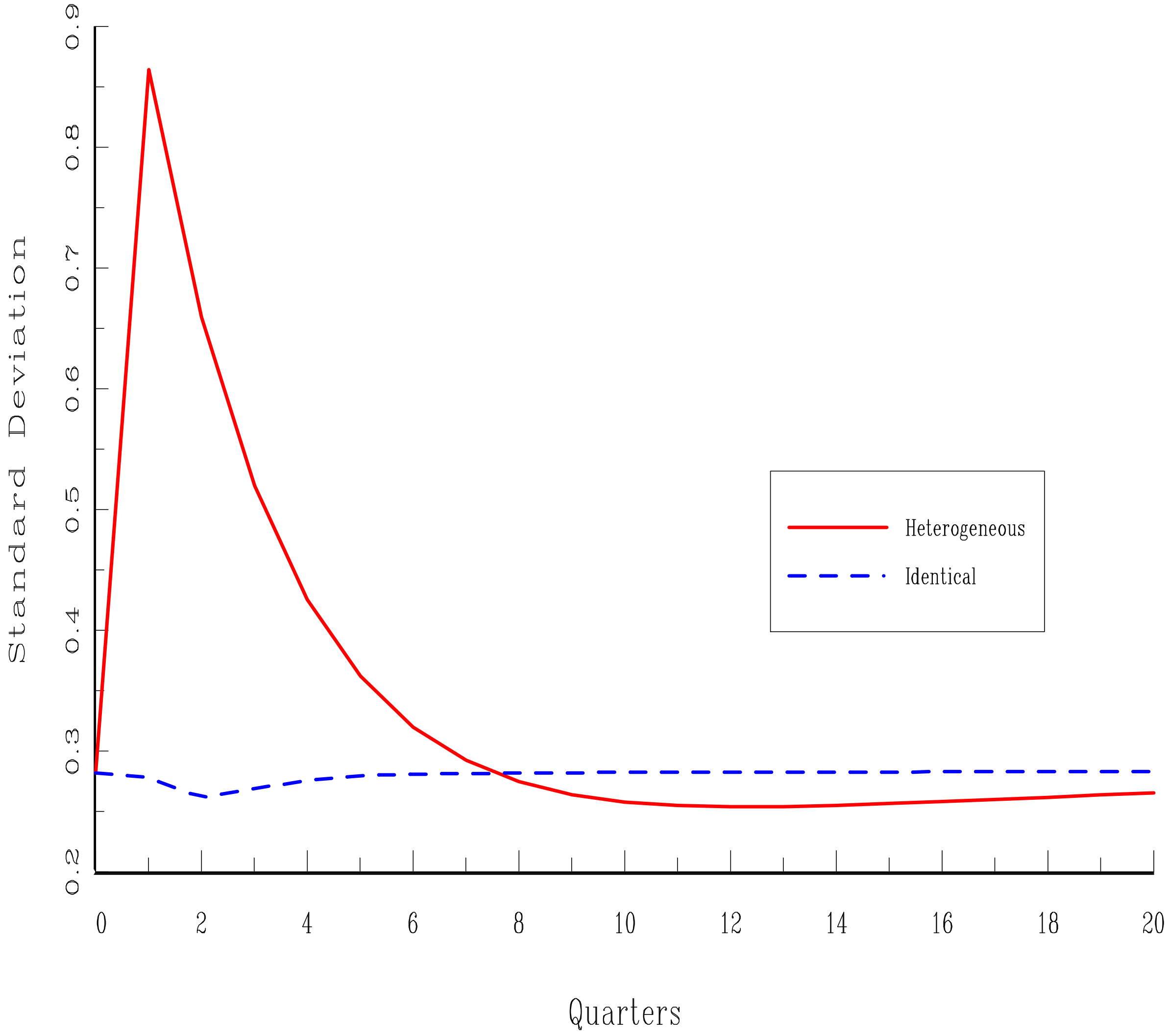


Figure 6: The Importance of Sectoral Shocks

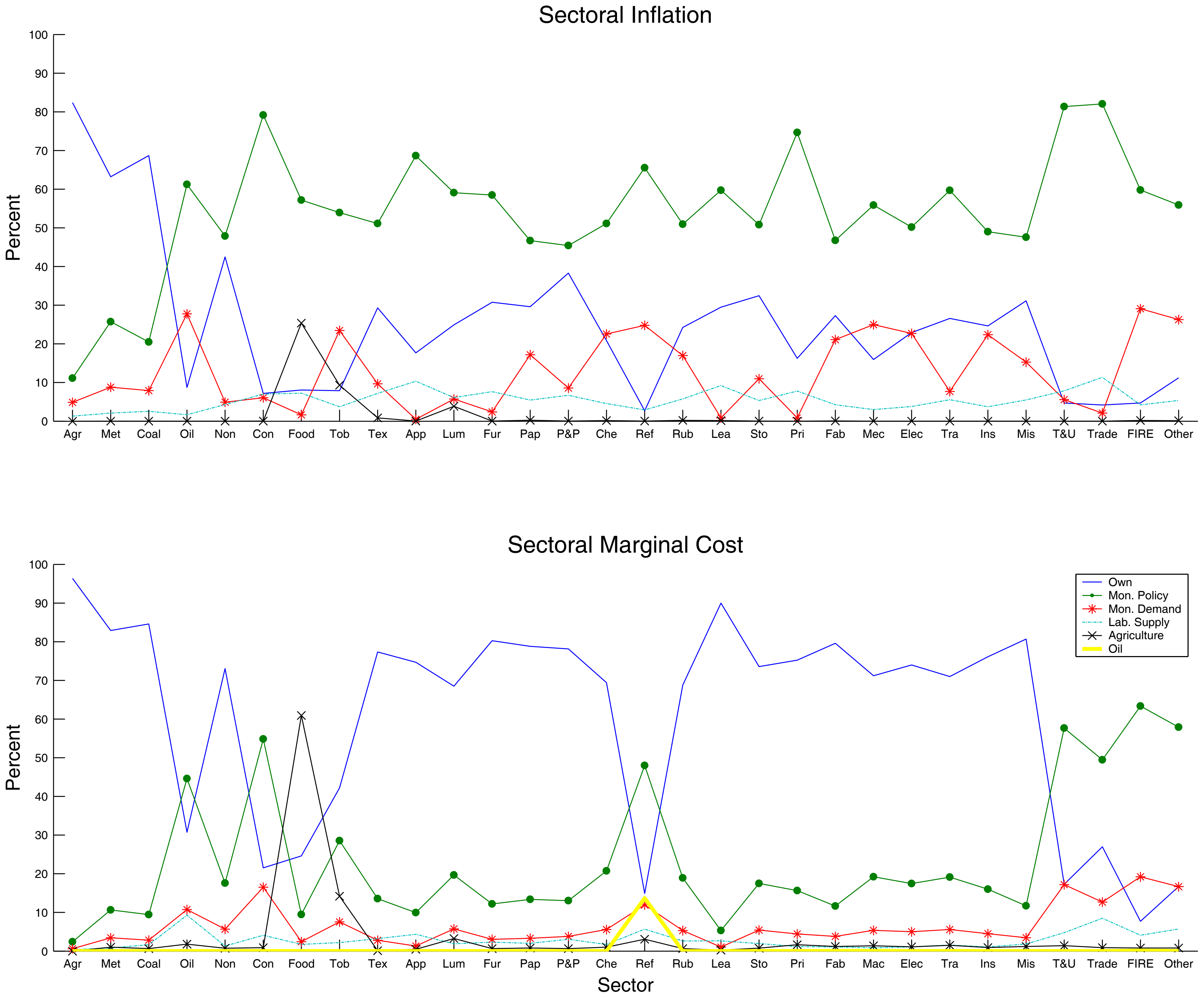
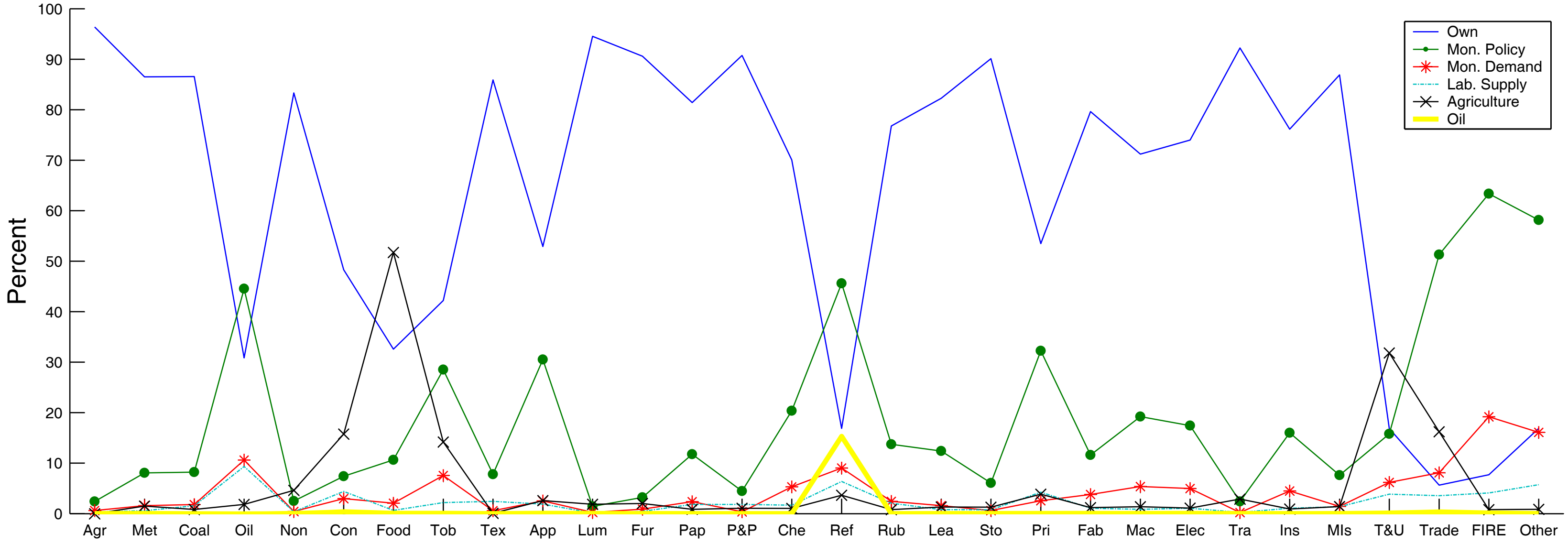


Figure 6: The Importance of Sectoral Shocks (cont.)

Sectoral Prices



Sectoral Output