Production Networks and the Propagation of Monetary Policy Shocks*

Ernesto Pasten[†], Raphael Schoenle[‡], and Michael Weber[§]

This version: March 2016

Abstract

We develop a multi-sector Calvo model with intermediate inputs to study the quantitative importance of heterogeneities in price rigidities, sector size, and input-output linkages and their interaction for the real effects of monetary policy shocks. We show theoretically real effects are bigger if the share of intermediate inputs is high or if sticky-price sectors are important suppliers to the rest of the economy, to flexible-price sectors, or to large sectors. Quantitatively, heterogeneity in input-output linkages contributes only marginally to the real effects of monetary policy shocks, whereas heterogeneity in the frequency of price adjustment creates large real effects of nominal shocks. Differences in consumption shares have an economically important effect on the total real effects. To reach those conclusions, we calibrate a 350-sector version of the model to the input-output tables from the Bureau of Economic Analysis and the micro-data underlying the producer price index from the Bureau of Labor Statistics to reach those conclusions. A less granular calibration with only 58 sectors understates the real effects of monetary policy by 25%, with a similar impact response of inflation. The large real effects reflect heterogeneity in price markups due to the different heterogeneities and a higher average level of markups, fully driven by the product market wedge.

JEL classification: E30, E32, E52

Keywords: Input-output linkages, multi-sector Calvo model, monetary policy

*We thank Carlos Carvalho and seminar participants at CREI, EEA 2015, FGV, Banque de France Pricing and Inflation Conference, Oxford, SED 2015, and Toulouse for valuable comments, as well as Menaka Hampole, Stephen Lamb, and Seongeun Kim for excellent research assistance. Pasten is grateful for the support of Universitï¿½ de Toulouse (Capitole) and Christian Hellwig's ERC Grant during his stays in Toulouse. Weber gratefully acknowledges financial support from the University of Chicago, the Neubauer Family Foundation, and the Fama–Miller Center.

[†]Central Bank of Chile and Toulouse School of Economics. e-Mail: ernesto.pasten@tse-fr.eu

[‡]Brandeis University. e-Mail: schoenle@brandeis.edu.

[§]Booth School of Business, University of Chicago. e-Mail: michael.weber@chicagobooth.edu.

I Introduction

Monetary policy shocks are central to understanding business-cycle fluctuations (see Ramey (2015)). Most transmission channels of nominal shocks to the real economy rely on some output prices being sticky in the short run, and the real effects of nominal shocks increase in heterogeneity in price stickiness (Carvalho (2006)). But tightly linked production networks are also a key feature of modern production economies. The network structure is potentially an important propagation mechanism for nominal shocks (Basu 1995), and asymmetry in sector size or input-output structure might contribute to aggregate fluctuations originating from idiosyncratic shocks (Gabaix (2011) and Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012)).

In this paper, we study quantitatively the interaction of heterogeneity in price stickiness, sector size, and input-output structure across sectors to understand how the interaction of these empirically prevalent heterogeneities affects the real effects and the propagation of monetary policy shocks. We develop a multi-sector New Keynesian model with intermediate input to address these questions. Firms set prices as in Calvo (1983) and use the output of other firms as intermediate inputs into production. We model the input-output structure as a round about network.

We show theoretically the real effects of monetary policy increase in the share of intermediate inputs, or if sticky-price sectors are important suppliers to the rest of the economy, to flexible-price sectors, or to large sectors.

Empirically, we calibrate a 350-sector version of the model to the input-output tables from the Bureau of Economic Analysis (BEA) and the micro-data underlying the producer price index from the Bureau of Labor Statistics (BLS) to quantitatively study the importance of the different degrees of heterogeneity across sectors. Heterogeneity in price stickiness is the main driver of the real effects of monetary policy shocks. The effects of heterogeneous input-ouput linkages are small compared to the effects of price stickiness. Heterogeneity in consumption shares increases the cumulative real effects of nominal shocks by 20%. We also find the 350-sector economy has a 25% larger real effect of monetary policy shocks than a less granular 58-sector model. The impact response of inflation, on the contrary, is similar in the two models. This finding cautions against drawing inference for the conduct of monetary policy from the response of inflation to monetary policy shocks.

The interaction of the different heterogeneities creates heterogeneity in price markups, raises the average level of markups, and results in larger inefficiencies in the economy. These inefficiencies are observationally equivalent to a countercyclical labor wedge (see Gali, Gertler, and Lopez-Salido (2007)). In our model, product market wedges are fully responsible for the inefficiencies, stressing the importance of product markets and price stickiness for business-cycle fluctuations (see Bils, Klenow, and Malin (2014)).

The size and interconnectedness of a sector and the interaction with frequencies of price adjustment matter for the real effects of monetary policy. This setup generates a rich set of theoretical predictions. Depending on these interactions, the economy in the extreme might resemble either a flex-price economy or an economy with uniformly rigid prices. We identify four distinct channels through which input-output linkages and the heterogeneities of sector size and price stickiness affect the marginal cost process. First, marginal costs of final-goods producers depend directly on the sector-specific input price index. Second, sector-specific wages depend indirectly on the input-output linkages because the optimal mix of inputs depends on the relative price of intermediate inputs and labor. Third and fourth, the heterogeneities across sectors in total production, value-added, and intermediate inputs create wedges between sectoral participation in total output, production, and total GDP that feed back into marginal costs. These channels interact in shaping the response to nominal shocks in a very intuitive way: How important is the output of a given sector for final-goods production? How flexible are the output prices of the goods the sector uses in production? How important is the sector as a producer for total consumption?

We develop intuition for the interaction of the three heterogeneities by gradually adding each heterogeneity, and prove results analytically when possible. We start with an economy that features input-output linkages that can be homogeneous or heterogeneous across sectors. Calvo parameters are homogeneous across sectors, and sectoral participation in GDP equals sectoral participation in total production. Input-output linkages amplify the real effects of monetary policy, as in Nakamura and Steinsson (2008), but heterogeneity in input-output linkages does not matter, because sectoral production and consumption shares contain no wedges. We show these results analytically.

We then add heterogeneity in Calvo parameters in the form of a mean-preserving spread. Heterogeneity in Calvo parameters results in a hump-shaped response. Flexible-price firms compete with sticky-price firms. Firms with flexible prices adjust prices in a staggered fashion and by less on impact compared to a model with homogeneous Calvo rates across sectors. Relative to a homogeneous network structure, however, we find heterogeneity in price stickiness amplifies the output response while heterogeneity in the input-output structure has no effect as long as outdegrees equal consumption shares.

Last, we allow for differences in sector weights in GDP and in total production. This additional degree of heterogeneity results in wedges between consumption prices and sectoral production prices, which influence sectoral marginal costs. Again, heterogeneity in input-output linkages can amplify or dampen the response of GDP to monetary policy shocks. For example, the economy may resemble a flexible-price economy depending the interaction of sector size, the importance of sectors as suppliers to other sectors, and sectoral price stickiness.

Intermediate inputs amplify the real effects of monetary policy, but heterogeneity in input-output linkages might either reinforce or dampen real effects, calling for a quantitative analysis, which we discuss above.

A central finding of this analysis is the inflationary response can be very similar across calibrations with different degrees of granularity, whereas the real effects of monetary policy might differ substantially. Specifically, we find a similar impact response of inflation to a monetary policy shown in our 350-sector benchmark economy and a less granular, 58-sector model. The 58-sector model understates the real effects of monetary policy, instead, by 25%.

A. Literature review

Our paper contributes to the monetary economics literature on the amplification role of input-output linkages through complementarities in price setting. Basu (1995) shows a roundabout production structure can magnify the importance of price rigidities through its effect on marginal costs, and results in larger welfare losses of demand-driven business cycles. Huang and Liu (2004) study the persistence of monetary shocks in a multi-sector model with roundabout production and fixed contract length. They show theoretically intermediate inputs amplify the importance of rigid prices with no impact on wage stickiness. Nakamura and Steinsson (2010) develop a multi-sector menu cost model and show in a calibration of a six-sector version that heterogeneity in price stickiness together with input-output linkages can explain persistent real effects of nominal shocks with moderate degrees of price stickiness. Carvalho and Lee (2011) show a multi-sector Calvo model with intermediate inputs can reconcile why firms adjust more quickly to idiosyncratic shocks than to aggregate shocks (see also Boivin et al. (2009) and Shamloo (2010)). Bouakez, Cardia, and Ruge-Murcia (2014) estimate a multi-sector Calvo model with production networks using aggregate and sectoral data, and find evidence for heterogeneity in frequencies of price adjustments across sectors. We extend this literature by allowing for empirically relevant degrees of heterogeneity in input-output linkages, sector size, and price stickiness, and study the importance of networks on the propagation of nominal shocks in a quantitative calibration of a 350-sector model.

A high degree of specialization is a key feature of modern production economies. Gabaix (2011) and Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012) show theoretically the network structure is potentially an important propagation mechanism for aggregate fluctuations originating from firm and industry shocks. Carvalho (2014) provides an overview of this fast-growing literature. Idiosyncratic shocks propagate through changes in prices. We study in a companion paper (see Pasten, Schoenle, and Weber (2016)) how price rigidities affect the importance of idiosyncratic shocks as an origin of aggregate fluctuations.

Other recent applications of production networks in different areas of macroeconmics are Bigio and Lao (2013), who study the amplification of financial frictions through production networks, Ozdagli and Weber (2016), who show empirically input-output linkages are a key propagation channel of monetary policy shocks to the stock market, and Herskovic (2015), who develops the asset-pricing implication of input-output linkages.

II Model

A. Firms

A continuum of monopolistically competitive firms exists in the economy operating in different sectors. We index firms by their sector, $k \in [0,1]$, and by $j \in [0,1]$. The set of consumption goods is partitioned into a sequence of subsets $\{\Im_k\}_{k=1}^{K}$ with measure $\{n_k\}_{k=1}^{K}$ such that $\sum_{k=1}^{K} n_k = 1$.

The production function of firm j in sector k is

$$Y_{kjt} = L_{kjt}^{1-\delta} Z_{kjt}^{\delta}, \tag{1}$$

where L_{kjt} is labor and Z_{kjt} is an aggregator of intermediate inputs

$$Z_{kjt} \equiv \left[\sum_{r=1}^{K} \omega_{kr}^{\frac{1}{\eta}} Z_{kjt}\left(r\right)^{1-\frac{1}{\eta}} \right]^{\frac{\eta}{\eta-1}}. \tag{2}$$

$Z_{kjt}(r)$ is the amount of goods firm j in sector k uses in period t as intermediate inputs from sector r. The aggregator weights $\{\omega_{kr}\}_{k,r}$ satisfy $\sum_{r=1}^{K} \omega_{kr} = 1$ for all sectors k. We allow these weights to differ across sectors, which is a central ingredient of our analysis.

$Z_{kjt}(r)$ is itself an aggregator of goods produced in sector r

$$Z_{kjt}\left(r\right) \equiv \left[n_r^{-1/\theta} \int_{\Im_r} Z_{kjt}\left(r, j'\right)^{1-\frac{1}{\theta}} dj' \right]^{\frac{\theta}{\theta-1}}. \tag{3}$$

$Z_{kjt}(r, j')$ is the amount of goods firm j' in sector r produces that firm k, j demands as input.

$Z_{kjt}(r)$ and $Z_{kjt}(r, j')$ solve

$$\begin{aligned} Z_{kjt}\left(r\right) &= \omega_{kr} \left(\frac{P_{rt}}{P_t^k} \right)^{-\eta} Z_{kjt}, \\ Z_{kjt}\left(r, j'\right) &= \frac{1}{n_r} \left(\frac{P_{rj't}}{P_{rt}} \right)^{-\theta} Z_{kjt}\left(r\right). \end{aligned}$$

$P_{rj't}$ is the price firm j' in sector r charges, P_{rt} is a sectoral price index, and P_t^k is an input-price index; we define both price indexes below. In a steady state, all prices are identical, and $\{\omega_{kr}\}_{r=1}^{K}$ is the share of costs firm k, j spends on inputs from sector r and, hence, equals the cell k, r in the Input-Output Tables (see the appendix). We refer to $\{\omega_{kr}\}_{r=1}^{K}$ as "I/O weights" or "I/O linkages." As a result, in a steady state, all n_r firms in sector r share the demand of firm k, j for goods produced in sector r equally.

Outside the steady state, a gap between the price of sector r, P_{rt}, and the aggregate price P_t^k relevant for firms in sector k distorts the share of sector r in the costs of firms in sector k. Similarly, price dispersion across firms within sector r determines the dispersion of demand of firms in sector k for goods in sector r.

Heterogeneity in I/O linkages, ω_{kr}, leads to differences in aggregate prices relevant for demand of intermediate inputs across sectors

$$P_t^k = \left[\sum_{r=1}^{K} \omega_{kr} P_{rt}^{1-\eta}\right]^{\frac{1}{1-\eta}}. \quad (4)$$

$$P_{rt} = \left[\frac{1}{n_r}\int_{\Im_r} P_{rj't}^{1-\theta} dj'\right]^{\frac{1}{1-\theta}} \quad (5)$$

defines the sectoral price index.

Firms set prices as in Calvo (1983), but we allow for differences in Calvo rates across sectors, $\{\alpha_k\}_{k=1}^K$. The objective of firm j, k is

$$\max_{P_{kjt}} \mathbb{E}_t \sum_{s=0}^{\infty} Q_{t,t+s}\alpha_k^s \left[P_{kjt}Y_{kjt+s} - MC_{kjt+s}Y_{kjt+s}\right]. \quad (6)$$

$MC_{kjt} = \frac{1}{1-\delta}\left(\frac{\delta}{1-\delta}\right)^{-\delta} A_{kt}^{-1} W_{kt}^{1-\delta}\left(P_t^k\right)^{\delta}$ are marginal costs after imposing the optimal mix of labor and intermediate inputs

$$\delta W_{kt} L_{kjt} = (1-\delta)\, P_t^k Z_{kjt}. \quad (7)$$

The optimal pricing problem takes the standard form

$$\sum_{s=0}^{\infty} Q_{t,t+s}\alpha_k^s Y_{kjt+s}\left[P_{kt}^* - \frac{\theta}{\theta-1} MC_{kjt+s}\right] = 0. \quad (8)$$

Y_{kjt+s} is the total output of firm k, j at period $t+s$, $Q_{t,t+s}$ is the stochastic discount factor between period t and $t+s$, and θ is the elasticity of substitution within sector.[1]

The optimal price for all adjusting firms within a given sector is identical, P_{kt}^*, allowing simple aggregation. The law of motion for sectoral prices is

$$P_{kt} = \left[(1-\alpha_k)\, P_{kt}^{*1-\theta} + \alpha_k P_{kt-1}^{1-\theta}\right]^{\frac{1}{1-\theta}} \text{ for } \forall k. \quad (9)$$

[1]We assume firms do not discriminate between demand from households and other firms.

B. Households

A large number of infinitely lived households exist. Households have a love for variety, and derive utility from consumption and leisure. Households supply all different types of labor. The representative household has additively separable utility in consumption and leisure and maximizes

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma} - 1}{1-\sigma} - \sum_{k=1}^{K} \int_{\Im_k} g_k \frac{L_{kjt}^{1+\varphi}}{1+\varphi} dj \right) \tag{10}$$

subject to

$$P_t C_t = \sum_{k=1}^{K} W_{kt} \int_{\Im_k} L_{kjt} dj + \sum_{k=1}^{K} \Pi_{kt} + I_{t-1} B_{t-1} - B_t. \tag{11}$$

The budget constraint states nominal expenditure equals nominal household income. C_t and P_t are aggregate consumption and aggregate prices, which we define below. L_{kjt} and W_{kt} are labor employed and wages paid by firm j in sector k. Households own firms and receive net income, Π_{kt}, as dividends. Bonds, B_t, pay a nominal gross interest rate of I_{t-1}.

Aggregate consumption is

$$C_t \equiv \left[\sum_{k=1}^{K} \omega_{ck}^{\frac{1}{\eta}} C_{kt}^{1-\frac{1}{\eta}} \right]^{\frac{\eta}{\eta-1}}, \tag{12}$$

where C_{kt} is the aggregation of sectoral consumption

$$C_{kt} \equiv \left[n_k^{-1/\theta} \int_{\Im_k} C_{kjt}^{1-\frac{1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}}. \tag{13}$$

C_{kjt} is the consumption of goods firm j in sector k produces.

We allow the elasticity of substitution across sectors η to differ from the elasticity of substitution within sectors θ. We also allow the consumption weights $\{\omega_{ck}\}$ to differ across sectors. The weights satisfy $\sum_{k=1}^{K} \omega_{ck} = 1$.

Households' demand for sectoral goods C_{kt} and firm goods C_{kjt} are:

$$\begin{aligned} C_{kt} &= \omega_{ck}\left(\frac{P_{kt}}{P_t^c}\right)^{-\eta} C_t, \\ C_{kjt} &= \frac{1}{n_k}\left(\frac{P_{kjt}}{P_{kt}}\right)^{-\theta} C_{kt}. \end{aligned}$$

We solve in the appendix for the steady state of the economy. We show the consumption weights $\{\omega_{ck}\}_{r=1}^K$ determine the steady-state shares of sectors in total consumption (or value-added production). In the following, we refer to $\{\omega_{ck}\}_{r=1}^K$ as "consumption shares." Outside the steady state, a gap between sectoral prices, $\{P_{kt}\}_{r=1}^K$, and aggregate consumption prices, P_t^c, distort the share of sectors in aggregate consumption.[2]

The consumption price index P_t^c is given by

$$P_t^c = \left[\sum_{k=1}^K \omega_{ck} P_{kt}^{1-\eta}\right]^{\frac{1}{1-\eta}}. \tag{14}$$

Sectoral prices follow

$$P_{kt} = \left[\frac{1}{n_k}\int_{\Im_k} P_{kjt}^{1-\theta} dj\right]^{\frac{1}{1-\theta}}. \tag{15}$$

C. Monetary policy

The monetary authority sets the short-term nominal interest rate, I_t, according to a Taylor rule:

$$I_t = \frac{1}{\beta}\left(\frac{P_t}{P_{t-1}}\right)^{\phi_\pi}\left(\frac{C_t}{\overline{C}}\right)^{\phi_y} e^{\mu_t}. \tag{16}$$

μ_t is a monetary shock following an AR(1) process with persistence ρ_μ.

Monetary policy reacts to aggregate-consumption inflation and aggregate consumption, which is the best proxy of value-added production (GDP) in the model.

[2]The measure of firms in sector k, n_k, and the consumption shares are related in equilibrium (see the appendix).

D. Equilibrium conditions and definitions

$$
\begin{aligned}
B_t &= 0, && (17)\\
L_{kt} &= \int_{\Im_k} L_{kjt} dj, && (18)\\
W_t &\equiv \sum_{k=1}^{K} n_k W_{kt}, && (19)\\
L_t &\equiv \sum_{k=1}^{K} L_{kt}, && (20)\\
Y_{kjt} &= C_{kjt} + \sum_{k'=1}^{K} \int_{\Im_{k'}} Z_{k'j't}\left(k, j\right) dj'. && (21)
\end{aligned}
$$

Equation (17) is the market-clearing condition in bond markets. Equation (18) defines aggregate labor in sector k. Equations (19) and (20) give aggregate wage (which is a weighted average of sectoral wages) and aggregate labor (which linearly sums up hours worked in all sectors). Equation (21) is the Walras law for the output of firm j in sector k.

III Heterogeneities and Marginal Costs

We derive a reduced-form system to develop intuition for how heterogeneity in price stickiness, I/O linkages, and sector size affect marginal costs and the real effects of monetary policy. Small letters denote log deviations from steady state.

The reduced-form system has $K+1$ equations and unknowns: value-added production c_t and sectoral prices $\{p_{kt}\}_{k=1}$. The first equation is

$$
\sigma \mathbb{E}_t \left[c_{t+1}\right] - \left(\sigma + \phi_c\right) c_t + \mathbb{E}_t \left[p^c_{t+1}\right] - \left(1 + \phi_\pi\right) p^c_t + \phi_\pi p^c_{t-1} = \mu_t, \qquad (22)
$$

which is a combination of the household Euler equation and the Taylor rule. The equation describes how variations in value-added production and aggregate consumption, p^c_t, share the monetary policy shock, μ_t.

p_t^c is given by

$$p_t^c = \sum_{k=1}^{K} \omega_{ck} p_{kt}. \tag{23}$$

K equations governing the variations in sectoral prices complete the system

$$\beta \mathbb{E}_t \left[p_{kt+1} \right] - (1+\beta) p_{kt} + p_{kt-1} = \kappa_k \left(p_{kt} - mc_{kt} \right), \tag{24}$$

where $\kappa_k \equiv (1-\alpha_k)(1-\alpha_k \beta) / \alpha_k$.

We see prices in sector k must decrease when markups in sector k are higher than in a steady state. The price response for a given variation in markups depends on κ_k. We allow for heterogeneity in price stickiness across sectors, which results in variation in the response of sectoral prices to markup variations through heterogeneity in κ_k. If prices in sector k are fully flexible, $\kappa_k \to \infty$, so $p_{kt} = mc_{kt}$. If prices in sector k are completely rigid, $\kappa_k \to 0$, so $p_{kt} = 0$.

A. The effect of I/O linkages on marginal cost

Heterogeneity in I/O linkages affect the system only through its effect on deviations in marginal costs. We now solve for the steady-state deviations of marginal costs and focus on the effect of I/O linkages. We distinguish between the use of intermediate inputs for production common across sectors (i.e., $\delta > 0$), and heterogeneous usage of intermediate inputs across sectors (i.e., $\omega_{kr} \neq \omega_{k'r}$ for all k, all $k' \neq k$, and all r).

A.1 Preliminary results

We now derive how I/O linkages affect key variables that we use extensively in the following analysis.

First, the measure of sectors $\{n_k\}_{k=1}^{K}$ depends on I/O linkages. As we show in the appendix,

$$n_k = \psi \omega_{ck} + (1-\psi) \zeta_{kt}, \tag{25}$$

where

$$\zeta_k \equiv \sum_{k'=1}^{K} n_{k't} \omega_{k'k}. \tag{26}$$

The measure n_k of sector k is the weighted average of the consumption share of sector

k, ω_{ck}, and the importance of sector k as a supplier to the economy, ζ_k. We refer to ζ_k as the "outdegree" of sector k in analogy to Acemoglu et al. (2012). The outdegree of sector k is the weighted sum of input shares of all sectors using the goods firms in sector k produce as intermediate inputs, $\omega_{k'k}$, with the measure of sectors determining the weights, $n_{k't}$. In a steady state, all firms are identical and we can interpret n_k as the size of sector k.

Without intermediate inputs ($\delta = 0$), $\psi \equiv \delta(\theta - 1)/\theta = 0$, and only consumption shares determine sector size. However, when firms use intermediate inputs for production ($\delta > 0$), heterogeneity in I/O linkages results in heterogeneity in sector size. The outdegree of sector k is higher when sector k is a supplier to many sectors or is a supplier of large sectors.

The vector $\aleph$ of sector sizes $\{n_k\}_{k=1}^K$ solves

$$\aleph = (1 - \psi)\left[\mathbb{I}_K - \psi\Omega'\right]^{-1}\Omega^C, \tag{27}$$

where $\mathbb{I}_K$ is the identity matrix of dimension K, Ω is the I/O matrix in a steady state with elements $\{\omega_{kk'}\}$, and Ω^C is the vector of consumption shares, $\{\omega_{ck}\}$.

Second, the relevant aggregate price for demand of intermediate inputs in sector k depends on I/O linkages,

$$p_t^k = \sum_{k'=1}^{K} \omega_{kk'} p_{k't}. \tag{28}$$

The sector-k aggregate price responds more to variation in prices in a sector k' when sector k' is a large supplier to sector k.

A.2 Direct effect on sectoral marginal costs

With intermediate inputs in production, sectoral marginal costs are a weighted average of sectoral wages, but also sector-relevant prices,

$$mc_{kt} = (1 - \delta) w_{kt} + \delta p_t^k. \tag{29}$$

Heterogeneity in I/O linkages enters through sector-k aggregate price, p_t^k. All else equal, an increase in the price of sector k' implies higher costs of intermediate inputs. This effect is stronger when sector k' is a large supplier of sector k.

A.3 Effect on sectoral wages

I/O linkages also affect sectoral wages $\{w_{kt}\}$, because the efficient mix of labor and intermediate inputs in equation (7) depends on relative input prices. The production function implicitly defines labor demand in sector k for a given level of production y_{kt}

$$y_{kt} = l_{kt} + \delta \left(w_{kt} - p_t^k \right). \tag{30}$$

In a model without I/O linkages, sectoral labor demand is inelastic after conditioning on sectoral production y_{kt}. Here, labor demand depends negatively on wages, because higher wages lead firms to substitute labor for intermediate inputs.

Combining the production function and sectoral labor supply yields

$$w_{kt} = \frac{1}{1+\delta\varphi} \left[\varphi y_{kt} + \sigma c_t + \delta\varphi \left(p_t^k - p_t^c \right) \right] + p_t^c. \tag{31}$$

The wedge between sector-k-relevant prices and consumption aggregate prices, $\left(p_t^k - p_t^c\right)$, captures the effect of heterogeneity in I/O linkages.

In a model without I/O linkages, wages respond one to one to variations in consumption aggregate prices p_t^c through their effect on labor supply. An increase in sector k' prices positively affects wages in sector k by the consumption share of sector k', $\omega_{ck'}$.

The same effect is present in the economy with I/O linkages. An increase in sector k' prices has an additional effect on sector k wages when the share of sector k' as a supplier of sector k is larger than its consumption share, that is when $\omega_{kk'} > \omega_{ck'}$. Intuitively, if sector k' is a large supplier to sector k, a positive variation in $p_{k't}$ has a larger effect on increasing the cost of intermediate inputs for firms in sector k, and firms increase the demand for labor.

A.4 Effect on sectoral demand

Next, we investigate how I/O linkages affect the transmission of variations in aggregate demand y_t into sectoral demand, $\{y_{kt}\}_{k=1}^K$.

Total demand for sector k is given by

$$y_{kt} = y_t - \eta \left[p_{kt} - (1-\psi)\, p_t^c - \psi \widetilde{p}_t\right], \tag{32}$$

where

$$\widetilde{p}_t \equiv \sum_{k=1}^{K} n_k p_t^k. \tag{33}$$

Sectoral demand depends on its relative price, p_{kt}, and a weighted average between consumption aggregate prices, p_t^c, and an "average sector-relevant" price, $\widetilde{p}_t$. $\widetilde{p}_t$ weights sector-relevant aggregate prices by the size of sectors. We can write the "average sector-relevant" price as

$$\widetilde{p}_t = \sum_{k=1}^{K} \zeta_k p_{kt}, \tag{34}$$

that is, the sum of variations in sectoral prices weighted by their outdegrees $\{\zeta_k\}_{k=1}^K$.

Following an increase in prices of a given sector k', the share of sector k in total demand increases in sector k' outdegree. This increase is stronger than the increase in an economy without intermediate inputs when $\zeta_{k'} > \omega_{ck'}$.

A.5 Effect on total demand

Finally, we solve for aggregate demand, y_t. Aggregating Walras law across all industries yields

$$y_t = (1-\psi)\, c_t + \psi z_t, \tag{35}$$

where z_t is the total amount of intermediate inputs. Intermediate inputs create a wedge between total production, y_t, and value-added production, c_t. The dynamics of z_t around the steady state depends on the heterogeneity in I/O linkages across sectors.

We solve for z_t, combining Walras law, the aggregate production function, aggregate labor supply, and the aggregation of efficient mixes between labor and intermediate inputs,

$$z_t = \frac{\left[(1+\varphi)(1-\psi) + \sigma(1-\delta)\right] c_t - (1-\delta)\left(\widetilde{p}_t - p_t^c\right)}{(1-\psi) + \varphi(\delta-\psi)}. \tag{36}$$

In an economy with no I/O linkages, $\delta = 0$, $\psi = 0$, and so $y_t = c_t$. With intermediate inputs, z_t varies positively with c_t: more value-added production requires more intermediate inputs. An increase in prices of a given sector k' has a negative effect on z_t when $\zeta_{k'} > \omega_{ck'}$. An increase in prices of big suppliers in the economy results in higher prices for intermediate inputs for many sectors and/or the bigger sectors. These sectors then substitute intermediate inputs for labor, and the aggregate demand for intermediate inputs decreases.

To simplify exposition, we write the relationship between y_t and c_t as

$$y_t = (1 + \psi \Gamma_c)\, c_t - \psi \Gamma_p \left(\widetilde{p}_t - p_t^c\right), \tag{37}$$

where $\Gamma_c \equiv \frac{(1-\delta)(\sigma+\varphi)}{(1-\psi)+\varphi(\delta-\psi)}$, $\Gamma_p \equiv \frac{1-\delta}{(1-\psi)+\varphi(\delta-\psi)}$.

B. Overall solution for log-linearized marginal costs

We combine equations that we derived in the previous subsections to express marginal costs in terms of value-added production and sectoral prices:

$$\begin{aligned} mc_{kt} \;=\; & \left[1 + \frac{(1-\delta)\,\varphi\eta}{1+\delta\varphi}\right] p_t^c + \delta \frac{1+\varphi}{1+\delta\varphi}\left(p_t^k - p_t^c\right) + (1-\delta)\,\frac{\varphi\psi\,(\eta - \Gamma_p)}{1+\delta\varphi}\left(\widetilde{p}_t - p_t^c\right) \\ & - \frac{(1-\delta)\,\varphi\eta}{1+\delta\varphi} p_{kt} + \frac{1-\delta}{1+\delta\varphi}\left[\sigma + \varphi\,(1+\psi\Gamma_c)\right] c_t. \end{aligned} \tag{38}$$

In an otherwise identical economy with no I/O linkages, marginal costs are given by

$$mc_{kt}^{\delta=0} = (1+\varphi\eta)\, p_t^c - \varphi\eta p_{kt} + (\sigma+\varphi)\, c_t. \tag{39}$$

The first line of equation (38) shows how sectoral prices affect sectoral marginal costs. In an economy with no I/O linkages, a positive deviation of sector k' prices increases marginal costs of other sectors through the consumption share $\omega_{ck'}$ of sector k'.

In an economy with I/O linkages, this effect of prices of other sectors on sector k marginal costs is mitigated. But I/O linkages create new channels. In particular, $p_{k't}$ has a stronger effect on mc_{kt} because (i) sector k' is a big supplier to sector k; that is, $\omega_{kk'} > \omega_{ck'}$ (second term on the right-hand side of equation (38)); and (ii) sector k' is a big supplier in the whole economy; that is, $\zeta_{k'} > \omega_{ck'}$ (third term on the right-hand side of equation (38)). The overall direct effect of variations in $p_{k't}$ on mc_{kt} is

$$\frac{(1-\delta)\left[1+(1-\psi)\,\varphi\eta+\psi\varphi\Gamma_p\right]}{1+\delta\varphi}\omega_{ck'}+\delta\frac{1+\varphi}{1+\delta\varphi}\omega_{kk'}+(1-\delta)\,\frac{\varphi\psi\,(\eta-\Gamma_p)}{1+\delta\varphi}\zeta_{k'}. \qquad (40)$$

We see from the fourth term on the right-hand side of equation (38) that sector k marginal costs decrease in sector k prices. The demand for production of sector k is a decreasing function in its price, and hence, in wages in sector k.

The fifth term on the right-hand side of equation (38) shows marginal costs increase in value-added production c_t.

IV Theoretical Results

In this section, we study the effect of sectoral heterogeneity in price stickiness and I/O linkages on the real effects of monetary policy shocks. We build intuition by studying special cases, and gradually add degrees of heterogeneity.

A. Homogeneous price stickiness

Assume Calvo parameters are homogeneous across sectors, $\alpha_k=\alpha\ \forall k$. This assumption allows us to aggregate sectoral price equations in equation (24) using consumption shares to get

$$\beta\mathbb{E}_t\left[\pi^c_{t+1}\right]-\pi^c_t=\kappa\left(p^c_t-\sum_{k=1}^{K}\omega_{ck}mc_{kt}\right)\equiv x_t. \qquad (41)$$

x_t is the aggregation of sectoral markups. We can interpret x_t as the inverse consumption-inflation pressure: positive x_t indicates negative consumption price inflation. The parameter $\kappa\equiv(1-\alpha)\,(1-\beta\alpha)\,/\alpha$ captures the sensitivity of prices to deviations of markups from the steady state. In the following, we build intuition using only x_t.

With equal price stickiness across sectors, monetary policy shocks affect all sectors equally, so $p_{kt}=p_{k't}$ for all k,k'. Therefore, $p^k_t=p^c_t=\widetilde{p}_t$ for all k regardless of consumption shares and heterogeneity in I/O linkages across sectors. This equality allows us to write the equation governing sectoral marginal costs (equation (38)):

$$-x_t=\frac{1-\delta}{(1+\delta\varphi)\kappa}\left[\sigma+\varphi\left(1+\psi\Gamma_c\right)\right]c_t. \qquad (42)$$

Value-added production c_t fully determines marginal costs. Our model has the same structure as the standard New Keynesian model. It differs in the parameter accompanying c_t: the steady-state share δ of intermediate inputs in firms' costs affects the inverse inflation pressure. With homogeneous price stickiness across sectors, we get a closed-form solution for c_t and π_t^c.

Proposition 1 *In an economy with homogeneous price stickiness across sectors,*

(i) The response of value-added production c_t and consumption inflation π_t^c to a monetary policy shock μ_t is given by

$$
\begin{aligned}
c_t &= \Lambda_{\mu c}\mu_t, \\
\pi_t^c &= \Lambda_{\mu\pi}\mu_t,
\end{aligned}
$$

where $\Lambda_{\mu c} = -\frac{1-\beta\rho}{(1-\beta\rho)\phi_c+\sigma(1-\rho)+(\phi_\pi-\rho)\Psi_c(\delta)\kappa}$, $\Lambda_{\mu\pi} = \frac{\overline{\kappa}_c(\delta)}{1-\beta\rho}\Lambda_{\mu c}$, *and* $\Psi_c(\delta) \equiv \frac{(1-\delta)[\sigma+\varphi(1+\psi\Gamma_c)]}{1+\delta\varphi}$.

(ii) The response of c_t is increasing in δ, the steady-state share of intermediate inputs in firms' costs.

(iii) Heterogeneity in I/O linkages is irrelevant for the response of c_t and π_t^c.

Proof. (i) Guess and verify using equations (22), (41), and (42).

(ii) Follows from comparative statics.

(iii) Follows from observing $\Lambda_{\mu c}$ and $\Lambda_{\mu\pi}$ do not depend on I/O linkages, $\{\omega_{kk'}\}_{k,k'=1}^{K}$.

■

Proposition 1 is a useful benchmark. Both value-added production, c_t, and consumption inflation, π_t^c, respond negatively to a contractionary monetary policy shock. The negative response of c_t increases in the share of intermediate inputs in production.

Prices are sticky, but wages are fully flexible. The response of marginal costs to a monetary shock becomes more sluggish when the share δ of intermediate inputs in firms' costs increases. The sluggishness in marginal costs due to the sluggishness in prices of intermediate inputs translates into sluggishness of output prices. Therefore, intermediate inputs amplify the real effects of monetary policy shocks (Basu (1995)), and the literature typically interprets intermediate inputs as a source of strategic complementarity in price setting (e.g., Nakamura and Steinsson (2010)).

Countervailing forces shape the response of consumption inflation π_t^c. On the one hand, a higher share of intermediate inputs results in a more sluggish response of π_t^c to a monetary shock. On the other hand, the stronger response of c_t results in a larger downward pressure on prices, π_t^c.

The results for the responses of inflation and consumption to a monetary policy shock also hold when we gradually add degrees of heterogeneity. We therefore develop intuition for our findings for more complicated economies, taking the response of π_t^c as given.

Another important result in Proposition 1 is the I/O structure of the economy is irrelevant for the propagation of monetary policy shocks. The real effects of monetary policy in a model with multiple sectors but identical price stickiness are identical to an economy with only one sector. For the real effects of monetary policy, the subset of firms with the same degree of price stickiness defines sectors, whereas I/O linkages within sectors are irrelevant.

B. Heterogeneous price stickiness but irrelevance of I/O linkages

We now study an economy with heterogeneous price stickiness across sectors in which the effects of heterogeneous I/O linkages are shut down. Heterogeneity in I/O linkages are irrelevant for the real effects of monetary policy shocks when outdegrees equal consumption shares, $\zeta_k = \omega_{ck}$.[3]

Aggregating all k price equations results in

$$\beta \mathbb{E}_t \left[\pi_{t+1}^c\right] - \pi_t^c = \sum_{k=1}^{K} \kappa_k \omega_{ck} \left(p_{kt} - mc_{kt}\right) \equiv x_t. \tag{43}$$

Comparing equation (43) to equation (41), we see heterogeneity in price stickiness enters now in the aggregation of sectoral markups.

Intuitively, sectoral prices absorb deviations of sectors' markups at different speeds, which the dynamics of inflation reflect. Therefore, we cannot reduce the system to two equations and two unknowns, c_t and π_t^c: we have to solve for c_t and $\{p_{kt}\}_{k=1}^K$ and do not have closed-form solutions. However, we still use x_t to develop intuition.

Heterogeneity in price stickiness implies sectoral prices do not respond equally to the same monetary policy shock. However, the sectoral weights of all aggregate prices are

[3] This condition does not imply the I/O matrix must be homogeneous.

identical under the conditions in this section, so $p_t^k = p_t^c = \widetilde{p}_t$ for all k.

Using equation (38), x_t solves

$$-x_t = \overline{\kappa}\left[\left(1 + \frac{(1-\delta)\,\varphi\eta}{1+\delta\varphi}\right)\sum_{k=1}^{K}\left(1 - \frac{\kappa_k}{\overline{\kappa}}\right)\omega_{ck}p_{kt} + \frac{1-\delta}{1+\delta\varphi}\left[\sigma + \varphi\left(1+\psi\Gamma_c\right)\right]c_t\right]. \quad (44)$$

where $\overline{\alpha} = \sum_{k=1}^{K}\omega_{ck}\alpha_k$ and $\overline{\kappa} = \sum_{k=1}^{K}\omega_{ck}\kappa_k$ with $\kappa_k \equiv (1-\alpha_k)(1-\beta\alpha_k)/\alpha_k$. Carvalho and Schwartzman (2015) show firms in flexible-price sectors change prices more often than firms in sticky-price sectors, but the first price change after a monetary shock captures the largest part of the overall response to the shock. Therefore, aggregate-consumption prices are more sticky compared to an economy with equal price stickiness across sectors, which amplifies the real effects of monetary policy shocks.

Proposition 2 *When heterogeneity in I/O linkages are irrelevant, more heterogeneity in price stickiness across sectors amplifies monetary non-neutrality.*

Proof.

See the appendix.

■

C. The general case

We now study an economy with heterogeneous price stickiness across sectors and no restriction on I/O linkages across sectors. Equation (43) still gives the response of consumer price inflation, but the expression for sectoral marginal costs changes.

The response of x_t to a monetary policy shock is

$$-x_t = \overline{\kappa}\left[\begin{array}{c}\left(1+\frac{(1-\delta)\varphi\eta}{1+\delta\varphi}\right)\sum_{k=1}^{K}\left(1-\frac{\kappa_k}{\overline{\kappa}}\right)\omega_{ck}p_{kt} + \frac{\delta(1+\varphi)}{1+\delta\varphi}\sum_{k=1}^{K}\frac{\kappa_k}{\overline{\kappa}}\omega_{ck}\left(p_t^k - p_t^c\right)\\ +\left(1-\delta\right)\frac{\varphi(\psi\eta+\delta\Gamma_p)}{1+\delta\varphi}\sum_{k=1}^{K}\left(\zeta_k-\omega_{ck}\right)p_{kt} + \frac{1-\delta}{1+\delta\varphi}\left[\sigma+\varphi\left(1+\psi\Gamma_c\right)\right]c_t\end{array}\right]. \quad (45)$$

The second and third terms of equation (45) are the new relative to the previous case (equation (44)). The second term is positive after a contractionary monetary policy shock when sectors with sticky prices are big suppliers to sectors with high consumption shares and/or flexible-price sectors (those with the high κ_k). If the second term is positive, a given variation in x_t results in a stronger variation of valued added, c_t. Intuitively, the real effects of monetary policy shocks are stronger when the marginal costs of the most flexible-price sectors are more sticky.

The third term of equation (45) is also positive after a contractionary monetary policy shock if sectors with outdegrees higher than consumption shares are the most sticky-price sectors.

The next proposition summarizes our findings.

Proposition 3 *The real effects of monetary policy shocks are bigger if*

(i) the share of intermediate inputs is high,

(ii) sectors with large outdegrees have the most sticky prices, and

(iii) sectors with the most sticky prices are big suppliers of sectors with high consumption shares and/or the most flexible sectors.

Proof.

See the appendix. ■

Heterogeneity can strengthen or dampen monetary non-neutrality, and the net effect is thus an empirical question, which we investigate in section VI.

V Data

This section describes the data we use to construct the input-output linkages, and the micro-pricing data we use to construct measures of price stickiness at the sectoral level.

A. Input and output Tables

The Bureau of Economic Analysis (BEA) produces I/O tables detailing the dollar flows between all producers and purchasers in the United States. Producers include all industrial and service sectors, as well as household production. Purchasers include industrial sectors, households, and government entities. The BEA constructs the I/O tables using Census data that are collected every five years. The BEA has published I/O tables every five years beginning in 1982 and ending with the most recent tables in 2012. The I/O tables are based on NAICS industry codes. Prior to 1997, the I/O tables were based on SIC codes.

The I/O tables consist of two basic national-accounting tables: a "make" table and a "use" table. The make table shows the production of commodities by industry. Rows present industries, and columns present the commodities each industry produces. Looking across columns for a given row, we see all the commodities a given industry produces. The sum of the entries comprises industry output. Looking across rows for a given column, we see all industries producing a given commodity. The sum of the entries adds up the output of a commodity. The use table contains the uses of commodities by intermediate and final users. The rows in the use table contain the commodities, and the columns show the industries and final users that utilize them. The sum of the entries in a row is the output of that commodity. The columns document the products each industry uses as inputs and the three components of "value added": compensation of employees, taxes on production and imports less subsidies, and gross operating surplus. The sum of the entries in a column adds up to industry output.

We utilize the I/O tables for 2002 to create an industry network of trade flows. The BEA defines industries at two levels of aggregation: detailed and summary accounts. We use both levels of aggregation to create industry-by-industry trade flows.

The BEA provides concordance tables between NAICS codes and I/O industry codes. We follow the BEA's I/O classifications with minor modifications to create our industry classifications. We account for duplicates when NAICS codes are not as detailed as I/O codes. In some cases, an identical set of NAICS codes defines different I/O industry codes. We aggregate industries with overlapping NAICS codes to remove duplicates.

We combine the make and use tables to construct an industry-by-industry matrix which details how much of an industry's inputs other industries produce.

We use the make table ($MAKE$) to determine the share of each commodity c that each industry i produces. We define the market share ("$SHARE$") of industry i's production of commodity c as

$$SHARE = MAKE \odot (\mathbb{I} \times MAKE)^{-1}_{i,j}, \tag{46}$$

where $\mathbb{I}$ is a matrix of 1s with suitable dimensions.

We multiply the share and use tables (USE) to calculate the dollar amount that industry i sells to industry j. We label this matrix revenue share ($REVSHARE$), which is a supplier industry-by-consumer industry matrix,

$$REVSHARE = (SHARE \times USE). \tag{47}$$

We use the revenue share matrix to calculate the percentage of industry j's inputs purchased from industry i and label the resulting matrix $SUPPSHARE$:

$$SUPPSHARE = REVSHARE \odot ((MAKE \times \mathbb{I})^{-1}_{i,j})^{\top}. \tag{48}$$

The input-share matrix in equation (48) is an industry-by-industry matrix and therefore consistently maps into our model. The direct-requirements table is a commodity-by-industry matrix, and the mapping to our theoretical model is therefore less straightforward. A commodity-by-commodity direct-requirements table would be an alternative to our approach of modeling input-output relations, but is not readily available. We report calibration results using direct requirements in the appendix for comparison with the literature (see, e.g., Acemoglu et al. (2012)).

B. Price stickiness data

We use the confidential microdata underlying the producer price data (PPI) from the BLS to calculate the frequency of price adjustment at the industry level.[4] The PPI measures changes in selling prices from the perspective of producers, and tracks prices of all goods-producing industries, such as mining, manufacturing, and gas and electricity, as well as the service sector.[5]

The BLS applies a three-stage procedure to determine the individual sample goods. In the first stage, to construct the universe of all establishments in the United States, the BLS compiles a list of all firms filing with the Unemployment Insurance system. In the second and third stages, the BLS probabilistically selects sample establishments and goods based on either the total value of shipments or the number of employees. The BLS collects prices from about 25,000 establishments for approximately 100,000 individual

[4]The data have been used before in Nakamura and Steinsson (2008), Goldberg and Hellerstein (2011), Bhattarai and Schoenle (2014), Gilchrist, Schoenle, Sim, and Zakrajšek (2015), Gorodnichenko and Weber (2016), Weber (2015), and D'Acunto, Liu, Pflueger, and Weber (2016).

[5]The BLS started sampling prices for the service sector in 2005. The PPI covers about 75% of the service sector output. Our sample ranges from 2005 to 2011.

items on a monthly basis. The BLS defines PPI prices as "net revenue accruing to a specified producing establishment from a specified kind of buyer for a specified product shipped under specified transaction terms on a specified day of the month." Prices are collected via a survey that is emailed or faxed to participating establishments. Individual establishments remain in the sample for an average of seven years until a new sample is selected to account for changes in the industry structure.

We calculate the frequency of price adjustment at the goods level, FPA, as the ratio of the number of price changes to the number of sample months. For example, if an observed price path is \$10 for two months and then \$15 for another three months, one price change occurs during five months, and the frequency is 1/5. We aggregate goods-based frequencies to the BEA industry level.

The overall mean monthly frequency of price adjustment is 22.15%, which implies an average duration, $-1/ln(1 - SAU)$, of 3.99 months. Substantial heterogeneity is present in the frequency across sectors, ranging from as low as 4.01% for the semiconductor manufacturing sector (duration of 24.43 months) to 93.75% for dairy production (duration of 0.36 months).

VI Calibration

We calibrate a 350-sector version of the model of section II. We use the make and use tables from the BEA to construct input shares across sectors (see section V). In total, we have three sources of heterogeneity: different combinations of intermediate inputs for production, different sector sizes, and heterogeneous Calvo rates across sectors. We measure sector size as a sector's share of value added in total value added. We construct sectoral frequencies of price adjustment using the micro-data underlying the PPI at the BLS. The granularity of the input-output data determines the definition of sectors for the PPI data. We calibrate our model at different levels of detail to analyze how the different degrees of heterogeneity interact. Carvalho (2006) shows a more granular definition of sectors results in larger real effects of monetary policy. Lucas (1977) instead argues that finer definitions of sectors lowers the aggregate effects of idiosyncratic shocks. We discuss the most granular case with 350 sectors in detail below and delegate a 58-sector model to the appendix.

The distribution of the frequency of price changes that goes into our calibration is fat-tailed: Figure 1 plots the unweighted sectoral frequencies of price adjustment for a 350-sector model. We see a large fraction of sectors having a mean monthly frequency of price adjustment of 0.1. The frequency contains a large right tail, which is a novel feature of our paper. Previous papers studied heterogeneity only at more aggregate levels and did not have a large, pronounced right tail in the frequency distribution. We study the impact of heavy tails in the frequency distribution below.

We calibrate the model at monthly frequency using standard parameter values in the literature (see Table 2). The coefficient of relative risk aversion σ is 1, and $\beta = 0.9975$ implying an annual risk-free interest rate of 3%. We set $\phi = 2$, implying a Frisch elasticity of labor supply of 0.5. We set θ, the average share of inputs in the production function to 0.5, in line with Basu (1995) and empirical estimates. We set the within-sector elasticity of substitution θ to 6, implying a steady-state markup of 20%, and the across-sector elasticity of substitution η to 2 in line with Carvalho and Lee (2011). We set the parameters in the Taylor rule to standard values of $\phi_\pi = 1.24$ and $\phi_c = 0.33/12$ (see Rudebusch (2002)). The persistence of monetary and (idiosyncratic) technology shocks are $\rho = 0.9$. We investigate the robustness of our findings to permutations in parameter values below.

A. Monetary policy shocks

In this section, we study the response of consumption, inflation, and real marginal costs to a 1% monetary policy shock. Our benchmark is a homogeneous model economy with homogeneous Calvo rates equal to the average Calvo rate, equal sector sizes, and input-output structure. We develop step-wise intuition analogous to section IV.

Our main empirical result is that heterogeneity in price stickiness is the main driver behind real effects of monetary policy. At the same time, the interaction of heterogeneous price stickiness, sector size, and input-output linkages can lower or amplify real effects, but only by small amounts. This result depends on the level of granularity, as well as the specification of the monetary policy rule. The response of inflation is also mainly driven by heterogeneity in the frequency of price changes across sectors, but little by heterogeneity in sector size or input-output linkages.

We calibrate six different cases to arrive at our results. We start with an economy with perfectly flexible prices, in which consumption and input-output linkages are homogeneous, and add one kind of heterogeneity at a time. Table 3 lists the different combinations of frequencies of price adjustments across sectors, sector sizes, and input-output linkages we study. Table 4 and Figure 2 show our results.

In our first case, prices are fully flexible and adjust fully on impact. We allow for the existence of input-output linkages, but we constrain them to be homogeneous and uniform. When all sectors have the same degree of price stickiness, the monetary shock affects all sectors equally, and consumption prices, p_t^c, and sector-relevant prices, p_t^k, are identical, as Proposition 1 discusses. Our model boils down to a textbook New Keynesian model in which the state-share of intermediate inputs, δ, also affects the response of consumption. In a New Keynesian model with fully flexible prices, prices fully absorb the monetary policy shock, and we do not see any effect on real consumption or marginal costs (red solid lines in Figure 2).

We add homogeneous price stickiness across sectors that is equal to a consumption-share weighted average in the economy of 18.35% in case 2. We know from the discussion of case 1 that our model behaves like a standard New Keynesian model. Price stickiness reduces the impact response of inflation by more than 40% (-1.64 vs. -2.94, see Table 4), and leads to a large impact drop in consumption of 3.46%. Both the inflation and consumption responses are persistent. Figure 2 shows the response in the red lines marked by x.

We do not study the interaction of homogeneous price stickiness, heterogeneous sector size, and heterogeneous input-output structure. We know from Proposition 1 that the response of consumption and inflation is independent from heterogeneity in sector size and input-output structure when price stickiness is homogeneous across sectors.

Next, we introduce in case 3 heterogeneity in price stickiness, keeping sector size and input-output structure homogeneous. As a result, sectoral prices react differently to a monetary shock, because of the heterogeneity in price stickiness. Under the assumptions of this case, however, sectoral weights of all aggregate prices are the same, so that $p_t^k = p_t^c = \widetilde{p}_t$ for all sectors k, and the wedge between price indices is absent.

What is the effect of heterogeneity of price stickiness? We see in Figure 2 (blue solid line) the negative selection effect introduced in Carvalho and Schwartzman (2015) dominates any of the other factors that influence markups, and real effects of monetary policy are substantially larger and the price effect is muted.[6] The real effects of monetary policy increase by more than 60%, and the cumulative consumption response more than doubles compared to an economy with homogeneous but equal average price stickiness (see Table 4). The inflation response, instead, is substantially muted (see blue dashed line in Figure 2). Our results confirm the intuition for economies with strategic complementarity in price setting of Carvalho and Schwartzman (2015) and Nakamura and Steinsson (2010).

Case 4 introduces heterogeneity in consumption weights. Input-output linkages are also heterogeneous but equal to consumption weights, $\omega_{kk'} = \omega_{ck}$. This assumption implies outdegrees equal the weight of sector k in consumption, $\zeta_k = \omega_{ck}$, and hence the aggregate consumption price index, p_t^c, and sector-k aggregate price index, p_t^k, are equal for all sectors k. As a result, input-output linkages do not affect the total markup in the economy, x_t, and hence consumption and inflation. Still, allowing for heterogeneity in consumption weights on impact increases the real effects of monetary policy by 10% and reduces the response of inflation by 3% relative to case 3. Overall, it increases the cumulative real effects by 20% and lowers the total response of inflation by more than 60% compared to heterogeneity in price stickiness only (compare blue asterisked line to blue dashed line in Figure 2).

Case 5 examines an economy in which input-output linkages are homogeneous but different from consumption weights. It is now no longer the case that $p_t^k = p_t^c$ and $\zeta_k = \omega_{ck}$, which opens up two additional wedges (see equation (45)). Real effects of monetary policy increase if sticky-price sectors are large suppliers to flexible-price sectors (making their marginal costs sticky) or to sectors important for aggregate consumption. Empirically, we do not find an economically significant effect of these two wedges on either output or inflation relative to the previous cases (see black line with plus sign in Figure 2).

Case 6 studies the interaction of all three heterogeneities: heterogeneity in price stickiness, sector size, and input-output linkages. The real effect of monetary policy and the inflation response is not qualitatively or quantitatively substantially different from the previous cases once we allow for heterogeneity in the frequency of price adjustment (see black dashed line in Figure 2). The reason the interaction of all three heterogeneities is not important comes from the empirical fact that sectoral price stickiness, sector size, and outdegrees are almost uncorrelated.

[6] Absent strategic interactions in price setting, selection effects characterize the real effects of monetary policy. Real effects are larger if older prices are less likely to change.

A.1 Summary and decomposition

To summarize, heterogeneity in price stickiness is the main driver of the real effects of monetary policy shocks in our calibration of a 350-sector economy to the empirical distribution of price stickiness from the BLS and the I/O structure from the BEA. I/O linkages and heterogeneity in sector size have some effect, but these effects are small compared to the effects of price stickiness. These findings suggest no strong systematic relationship between price flexibility and the importance of sectors as suppliers of flexible sectors, or the economy as a whole.

A decomposition of the real effects of monetary policy confirms this conclusion. Recall real effects are due to the following three components:

$$\begin{aligned} -x_t &= \Lambda_0(\delta)\sum_{k=1}^{K}(\overline{\kappa}-\kappa_k)\,\omega_{ck}p_{kt}+\delta\Lambda_1(\delta)\sum_{k=1}^{K}\kappa_k\omega_{ck}\left(p_t^k-p_t^c\right) \\ &\quad +\psi\Lambda_2(\delta)\,\overline{\kappa}\sum_{k=1}^{K}(\zeta_k-\omega_{ck})\,p_{kt}+\Lambda_3(\delta)\,c_t. \end{aligned}$$

Figure 3 displays the three components. Heterogeneity in price stickiness is responsible for most of the overall response of consumption (solid blue line). Heterogeneity in consumption shares and I/O linkages (dashed blue line and solid blue line marked by x; the second and third terms) both lower the response of consumption to a monetary policy shock in our baseline calibration, but both contributions are smaller in absolute terms. The figure confirms the results of the calibration and documents why heterogeneity in price stickiness drives most of the real effects of monetary policy.

A.2 Heterogeneity across sectors

Table 5 reports the cumulative real effects of monetary policy shocks for the 10 least (Panel A) and most (Panel B) responsive sectors for our different cases. We know from the discussion above and in section IV that all sectors are equally responsive in cases 1 and 2. Once we allow for heterogeneity in price stickiness in case 3, we see a somewhat heterogeneous response for the least responsive sectors in Panel A. The heterogeneity in real effects across sectors is substantially amplified for the most responsive sectors in Panel B. As we move across cases, some additional variation occurs, but overall, the dispersion changes little compared to the move from case 2 to case 3. This result confirms our findings above that heterogeneity in consumption shares or I/O structure might not amplify real effects of monetary policy shocks much. Panels C and D report the BEA industry classification codes of the most and least responsive sectors. We see the identity of the most and least responsive sectors varies substantially across cases, indicating the convolution of different heterogeneities is important.

A.3 Heterogeneity in markups

We now study the implication of heterogeneity in our model with respect to price markups. The introduction of an interaction of heterogeneity in price stickiness, sector size, and I/O linkages has important effects on price markups. These markups are interesting to consider because they represent a measure of inefficiency in the economy and are also equivalent to a countercyclical labor wedge (see Gali et al. (2007)), which in our case is entirely constituted by the product market wedge. Recent work by Bils, Klenow, and Malin (2014) points to the importance of the product market channel.[7] The level of markups in the full model is higher than in the homogeneous benchmark case, and markups display a rich, dynamic pattern. We report these findings in Figure 8.

The effect of fully interacted heterogeneities in our model becomes clear in comparison to the fully homogeneous economy. The markup responses of the homogeneous economy are summarized in Panel (a) of Figure 8. All sectoral responses are fast-decaying and identical across all percentiles. The initial magnitude is approximately a 3.5% deviation from the steady state. The half-life of the response is around eight periods.

By contrast, two differential facts emerge for the full model: first, the median sectoral response is substantially larger. The initial median markup response increases to approximately 6%. The solid, thick blue line summarizes the median response. The half-life of the median response is twice as long relative to the homogeneous case.

Second, substantial dispersion exists in the markup response. The top 5^{th} percentile of markups increases to over 10%; the bottom 5^{th} percentile does not increase above 2%. The sectoral markups also show very different dynamic patterns: the top percentiles show a hump-shaped response that is very persistent, with a half-life of more than 30

[7]Shimer (2009) has pointed out the absence of work on heterogeneity in the product market, a channel we are putting forward and expanding upon by allowing for interactions of heterogeneities.

periods. At the same time, the lowest percentiles decay exponentially with a half-life of less than one period. These very different price-markup responses directly result from the convolutions of the different underlying heterogeneities.

A.4 Robustness to monetary policy specification

In this subsection, we study the robustness of our baseline findings to variation in parameters of the Taylor rule and a specification with exogenous nominal demand, rather than closing the model with a Taylor rule. We report the results in Figure 4 and Table 6 for the same six cases we studied in the previous section.

As our first experiment, we increase ϕ_π, the systematic response of monetary policy to inflation in the Taylor rule, from a baseline value of 1.24 to 2.5.

We see in Figure 4 a similar response of inflation independent of whether we study heterogeneous or homogeneous price stickiness, sector size, and input-output structure. The impact response of inflation is, however, roughly cut in half, which comes from weaker demand effects. The inflation response tends to be more persistent with all three forms of heterogeneity, leading to larger cumulative inflation responses in an economy with $\phi_\pi = 2.5$ than in an economy with $\phi_\pi = 1.24$ (compare Panel B of Table 4 and Table 6).

The higher systematic response to inflation in the Taylor rule reduces the impact response of consumption by a factor of three across different cases (compare Panel A of Table 4 and Table 6). A model with heterogeneous price stickiness but homogeneous sector size and I/O structure has a similar impact response to an economy in which all three forms of heterogeneities interact (case 3 vs. case 6). A higher weight on inflation stabilization in the Taylor rule for a given demand shock results in a larger stabilization of output in the standard New Keynesian model. We see a similar result for the cumulative real effects of a demand shock in case 2, an economy with homogeneous price stickiness across sectors and no heterogeneity in sector size or I/O structure. Once we allow for heterogeneous price stickiness, the cumulative real effects of monetary policy shocks contract by 40%, with a more stringent response to inflationary pressure in the Taylor rule. Once we add heterogeneity in sector size and input-output structure, we even see larger cumulative real effects or a less stark drop in an economy with a more systematic response to inflation, despite smaller real effects on impact. We see in Panels A and C of Table 4 and Table 6 that the different forms of heterogeneity introduce a more sluggish and persistent response in consumption and real marginal costs, which explains the large real effects of demand shocks, despite the smaller effects on impact. This finding is reminiscent of the responder-nonresponder framework discussed in Carvalho (2006) and the selection effect of Carvalho and Schwartzman (2015).

Changes in the systematic response to output growth have little impact on the response of real consumption, inflation, or real marginal costs (not tabulated).

By contrast, our second experiment, a calibration of our model with all three heterogeneities, looks remarkably different when we close the model by positing exogenous nominal demand. Figure 6 and Table 8 report our findings. The solid red line represents our baseline response with the Taylor rule, and the red line marked by x represents the response for a model with exogenous nominal demand. Real marginal costs barely move in the model with exogenous demand, resulting in a small and transient impact response of inflation and a one-percentage-point response of consumption on impact. The impact response of consumption is smaller by a factor of six compared to the impact response with a Taylor rule.

A.5 Alternative specifications and variation in granularity

We now analyze how changes in parameters, granularity, and tails of the frequency distribution affect our findings. First, we study the effect of changes in risk aversion, σ, the Frisch elasticity, φ, the average input share in production, δ, the elasticity of substitution within and across sectors, η, θ, and the persistence of monetary policy shocks, ρ, in our full-blown model (case 6 in Table 3). Specifically, we set (baseline parameters in parentheses) $\sigma = 2(1)$, $\varphi = 1(2)$, $\delta = 0.7(0.5)$, $\eta = 6(2)$, $\theta = 10(6)$, and $\rho = 0.95(0.90)$. Figure 5 and Table 7 report our findings.

Overall, we see our results in the baseline calibration of Table 4 and Figure 2 are robust to variations in parameter values. The only exception is the increase of the coefficient of relative risk aversion, σ, from a baseline value of 1 to 2. The intratemporal rate of substitution from leisure to consumption determines the real wage. The drop in consumption results in a drop in the real wage, which increases in σ. Lower real wages lower the response of real marginal costs and the overall demand pressure.

Second, we compare the calibration of the 350-sector economy to a less granular

58-sector model. Figure 7 and Table 8 report our findings.[8] Real effects of monetary policy are 32% larger in the more granular 350-sector economy compared to the 58-sector calibration. By contrast, the impact response of inflation is only 13% smaller in the 350-sector economy compared to the 58-sector economy. This finding cautions against drawing inference for monetary policy from the response of inflation to shocks, because small-scale models might substantially underestimate the real effects. The differential response, however, is only true in a model with a Taylor rule, and vanishes once we close the model with exogenous nominal demand (see the appendix).

Third, the appendix also reports impulse response functions for a trimmed distribution in the frequency of price adjustment (see Figure A.6 and Figure A.7). Specifically, we compare the response of our baseline calibration for case 6 with a calibration that trims the 20% stickiest sectors and a calibration with a large left tail rather than a large right tail as the empirical distribution of the frequency of price adjustment. We keep the mean frequency of price adjustment identical across calibrations. The economy with a large left tail has the lowest real effects, whereas the other two economies result in similar responses.

VII Concluding Remarks

We theoretically and empirically study the interaction between heterogeneity in price stickiness, the I/O structure, and sector size for the real effects of monetary policy shocks. Although rich theoretical predictions exist, we find empirically that heterogeneity in price stickiness is the central mechanism for generating large and persistent real effects of nominal shocks. Consistently, we also document that small-scale models might substantially underestimate real effects even though the impact response of inflation is almost identical across different levels of granularity.

To reach these conclusions, we develop a multi-sector New Keynesian model with intermediate inputs, and calibrate a 350-sector version of the model to the I/O tables from the Bureau of Economic Analysis and the micro-data underlying the producer price index from the Bureau of Labor Statistics. Future work may consider the sensitivity of our results to endogenizing the price-adjustment process.

[8]We report robustness results for the 58-sector calibration in the online appendix.

References

Acemoglu, D., V. M. Carvalho, A. Ozdaglar, and A. Tahbaz-Salehi (2012). The network origins of aggregate fluctuations. *Econometrica 80*(5), 1977–2016.

Basu, S. (1995). Intermediate goods and business cycles: Implications for productivity and welfare. *The American Economic Review 85*(3), 512–531.

Bhattarai, S. and R. Schoenle (2014). Multiproduct firms and price-setting: Theory and evidence from u.s. producer prices. *Journal of Monetary Economics 66*, 178–192.

Bigio, S. and J. Lao (2013). Financial frictions in production networks. *Unpublished Manuscript, Columbia University*.

Bils, M., P. J. Klenow, and B. A. Malin (2014). Resurrecting the role of the product market wedge in recessions. Technical report, National Bureau of Economic Research.

Boivin, J., M. P. Giannoni, and I. Mihov (2009). Sticky prices and monetary policy: Evidence from disaggregated U.S. data. *The American Economic Review 99*(1), 350–384.

Bouakez, H., E. Cardia, and F. Ruge-Murcia (2014). Sectoral price rigidity and aggregate dynamics. *European Economic Review 65*, 1–22.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics 12*(3), 383–398.

Carvalho, C. (2006). Heterogeneity in price stickiness and the real effects of monetary shocks. *The B.E. Journal of Macroeconomics 2*(1), 1–56.

Carvalho, C. and J. W. Lee (2011). Sectoral price facts in a sticky-price model. *Unpublished Manuscript, PUC-Rio*.

Carvalho, C. and F. Schwartzman (2015). Selection and monetary non-neutrality in time-dependent pricing models. *Journal of Monetary Economics 76*, 141 – 156.

Carvalho, V. M. (2014). From micro to macro via production networks. *The Journal of Economic Perspectives 28*(4), 23–47.

D'Acunto, F., R. Liu, C. Pflueger, and M. Weber (2016). Flexible prices and leverage. *Unpublished manuscript, University of Chicago*.

Gabaix, X. (2011). The granular origins of aggregate fluctuations. *Econometrica 79*(3), 733–772.

Gali, J., M. Gertler, and J. D. Lopez-Salido (2007). Markups, gaps, and the welfare costs of business fluctuations. *The review of economics and statistics 89*(1), 44–59.

Gilchrist, S., R. Schoenle, J. Sim, and E. Zakrajšek (2015). Inflation dynamics during the financial crisis. *Unpublished Manuscript, Brandeis University*.

Goldberg, P. P. and R. Hellerstein (2011). How rigid are producer prices? *FRB of New York Staff Report*, 1–55.

Gorodnichenko, Y. and M. Weber (2016). Are sticky prices costly? Evidence from the stock market. *American Economic Review 106*(1), 165–199.

Herskovic, B. (2015). Networks in production: Asset pricing implications. *Unpublished Manuscript, UCLA*.

Huang, K. X. and Z. Liu (2004). Input–output structure and nominal rigidity: the persistence problem revisited. *Macroeconomic Dynamics 8*(2), 188–206.

Lucas, R. E. (1977). Understanding business cycles. In *Carnegie-Rochester conference series on public policy*, Volume 5, pp. 7–29. Elsevier.

Nakamura, E. and J. Steinsson (2008). Five facts about prices: A reevaluation of menu cost models. *Quarterly Journal of Economics 123*(4), 1415–1464.

Nakamura, E. and J. Steinsson (2010). Monetary non-neutrality in a multi-sector menu cost model. *Quarterly Journal of Economics 125*(3), 961–1013.

Ozdagli, A. and M. Weber (2016). Monetary policy through production networks: Evidence from the stock market. *Unpublished Manuscript, University of Chicago*.

Pasten, E., R. Schoenle, and M. Weber (2016). Nominal rigidities and the granular origins of aggregate fluctuations. *Unpublished manuscript, University of Chicago*.

Ramey, V. A. (2015). Macroeconomic shocks and their propagation. *Handbook of Macroeconomics, forthcoming*.

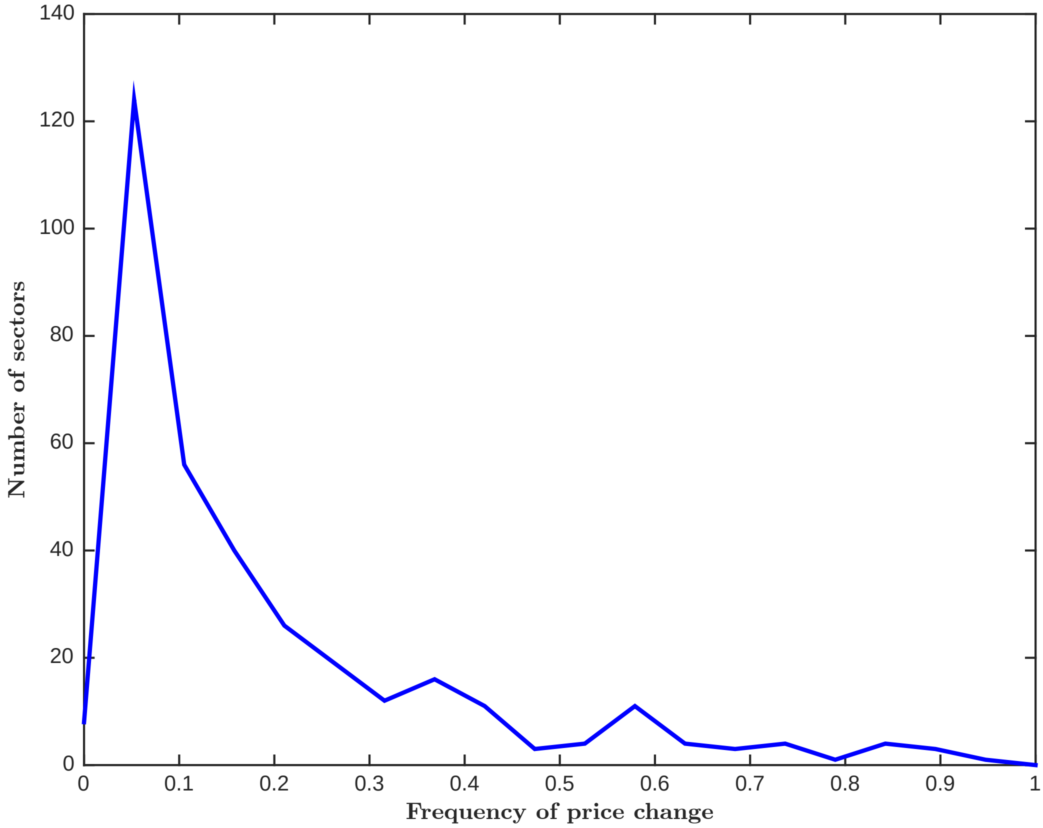
Rudebusch, G. D. (2002). Term structure evidence on interest rate smoothing and monetary policy inertia. *Journal of Monetary Economics 49*(6), 1161–1187.

Shamloo, M. (2010). Price setting in a model with production chains: Evidence from sectoral data. *IMF Working Papers*, 1–50.

Shimer, R. (2009). Convergence in macroeconomics: The labor wedge. *American Economic Journal: Macroeconomics 1*(1), 280–297.

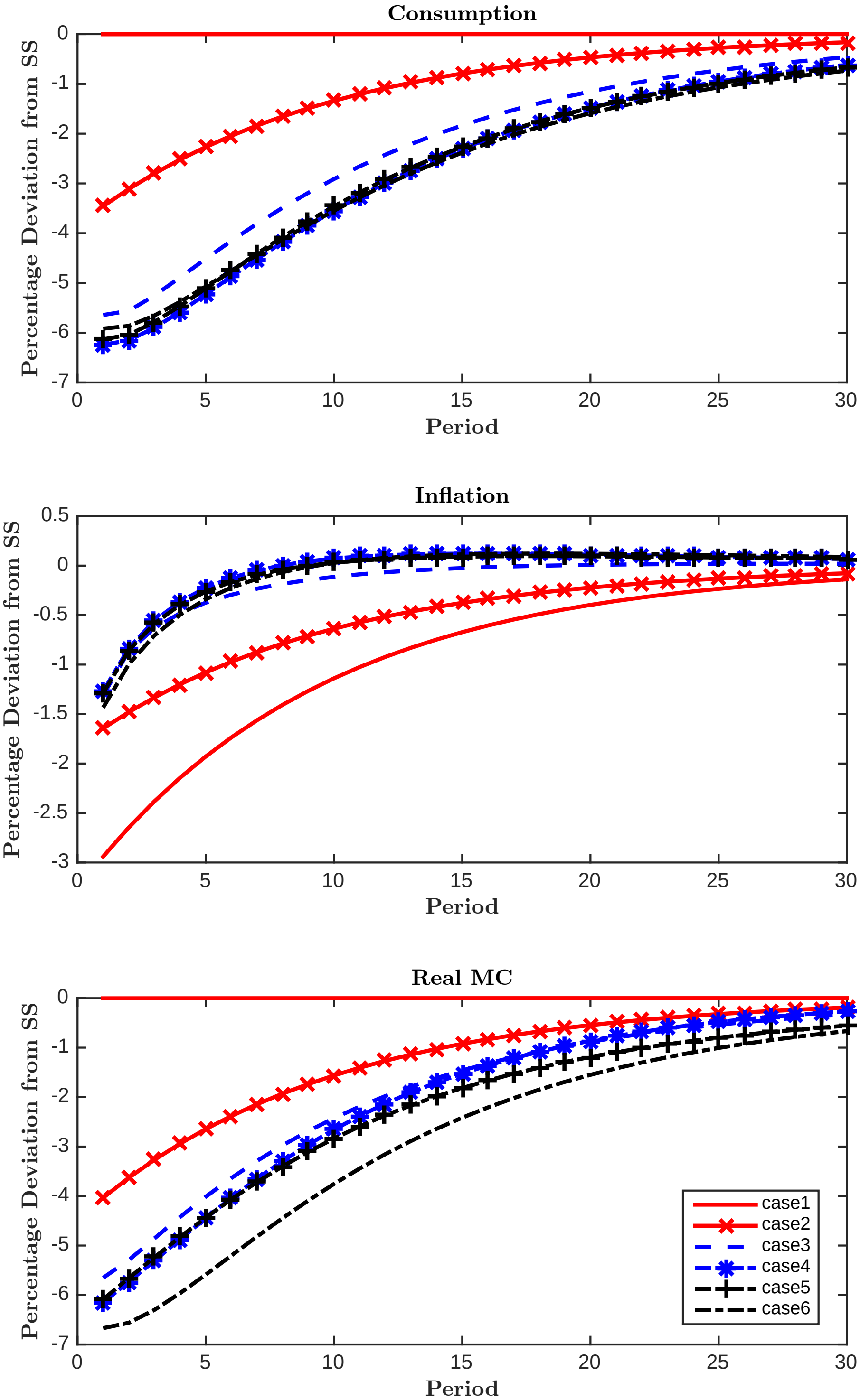
Weber, M. (2015). Nominal rigidities and asset pricing. *Unpublished manuscript, University of Chicago Booth School of Business*.

Figure 1: **Distribution of the Frequency of Price Adjustment**



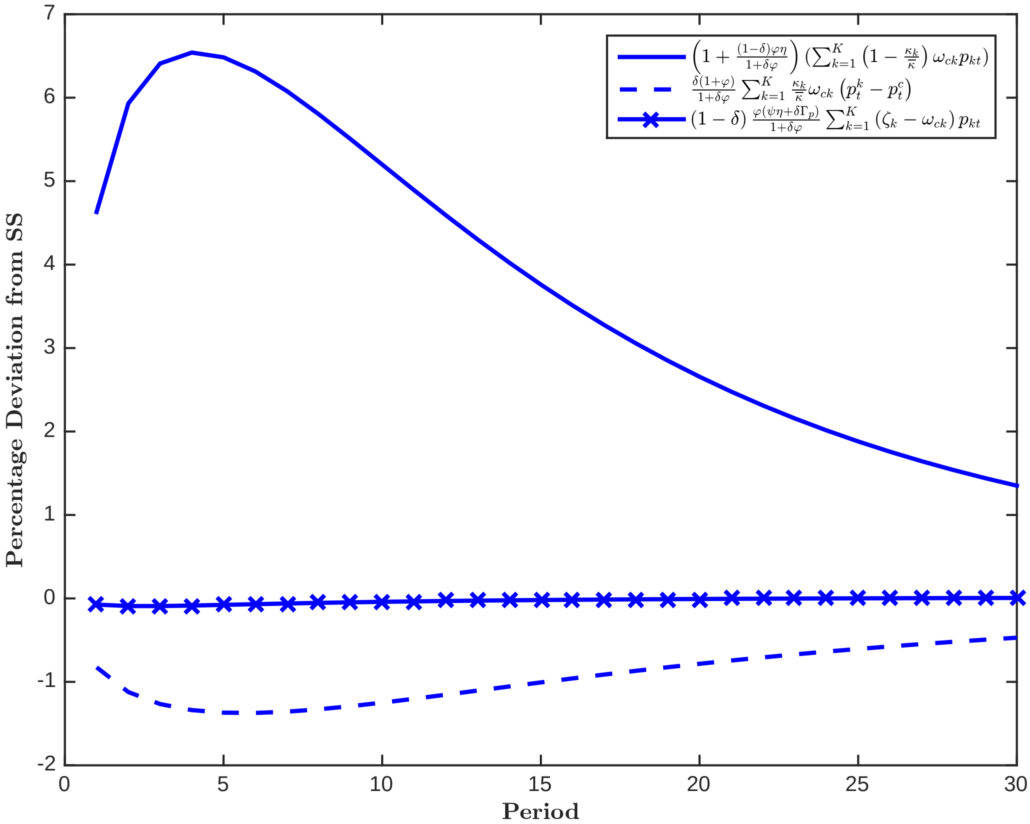
This figure plots the distribution of the frequency of price adjustment for a 350-sector model.

Figure 2: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock**



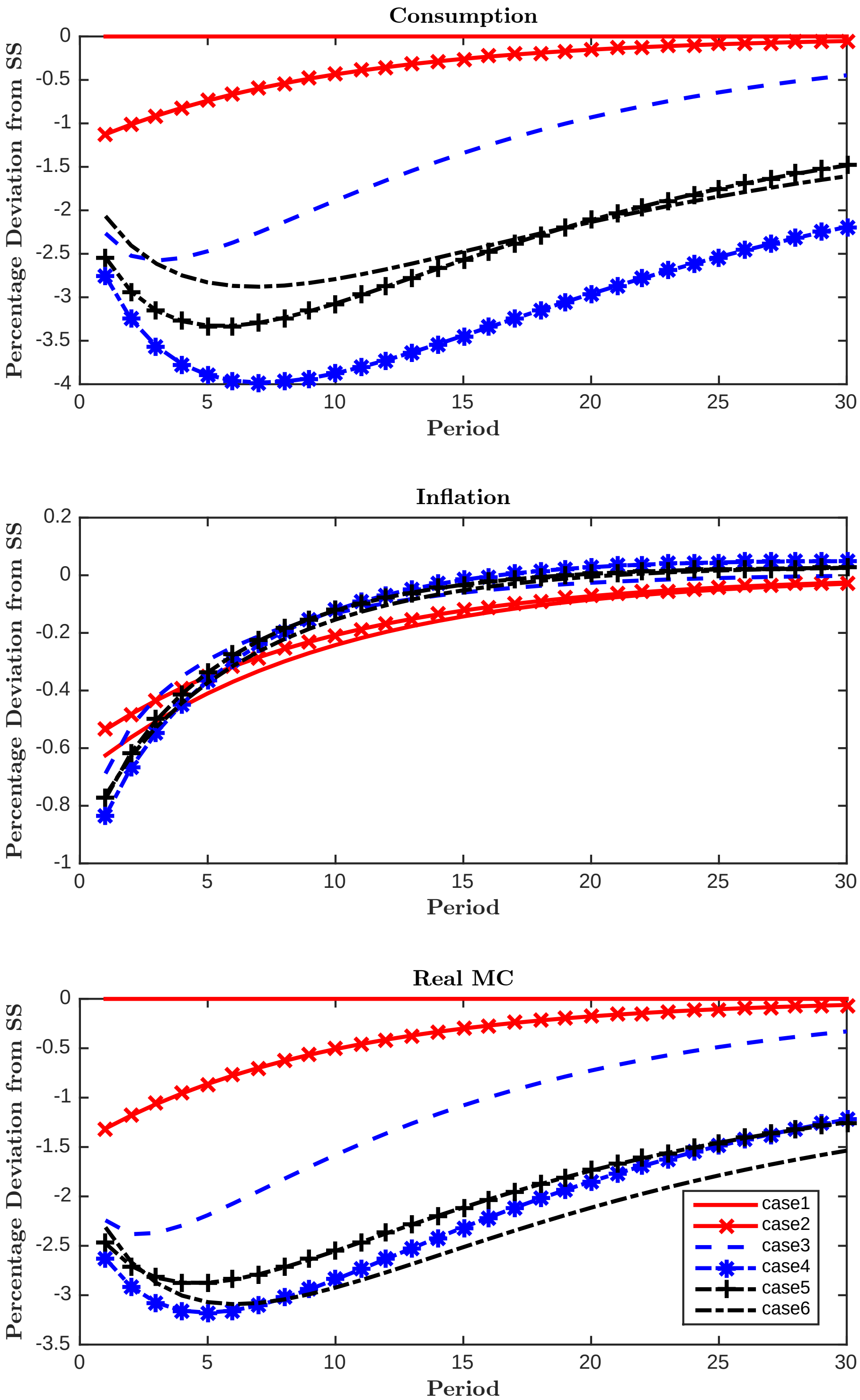
This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 350-sector model for different cases (see Table 3).

Figure 3: **Decomposition of the Overall Response of Markups into Components**



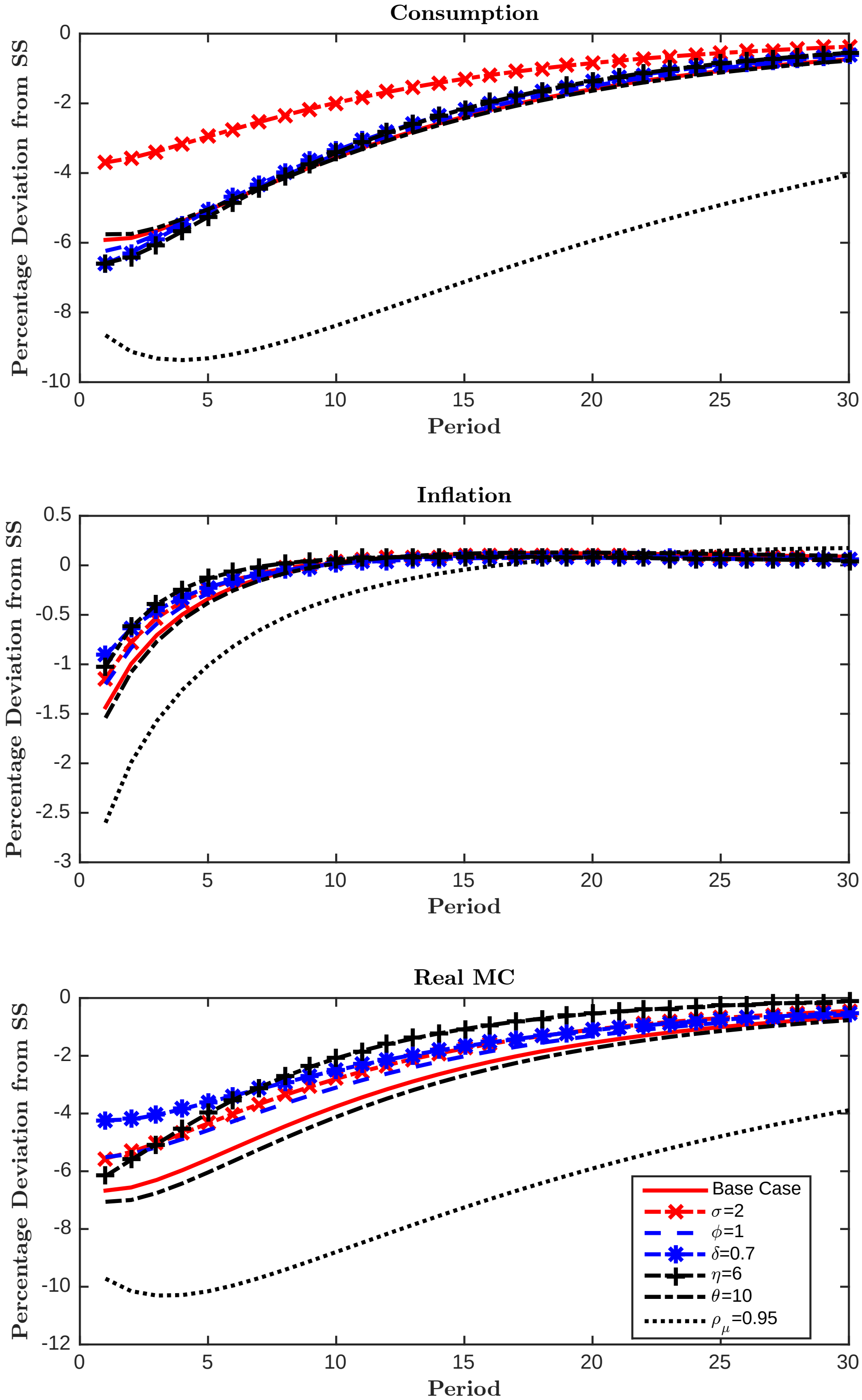
This figure decomposes the overall response of markups to a one-standard-deviation monetary policy shock for a 350-sector model into the three different components discussed in Section IV.

Figure 4: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock ($\phi_\pi = 2.5$)**



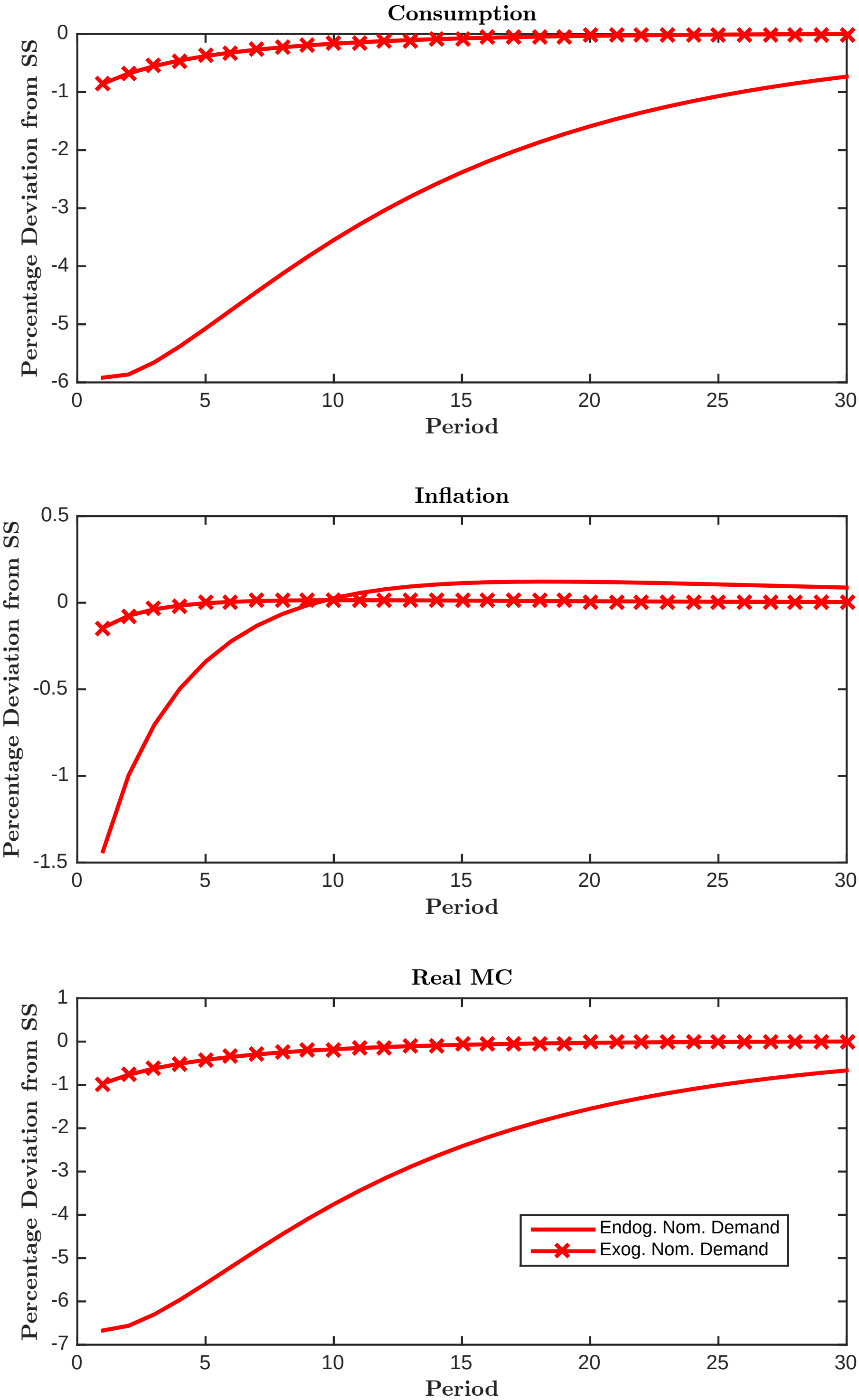
This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 350-sector model for different cases (see Table 3) with a coefficient on inflation in the Taylor rule of $\phi_\pi = 2.5$.

Figure 5: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock (variations in parameters)**



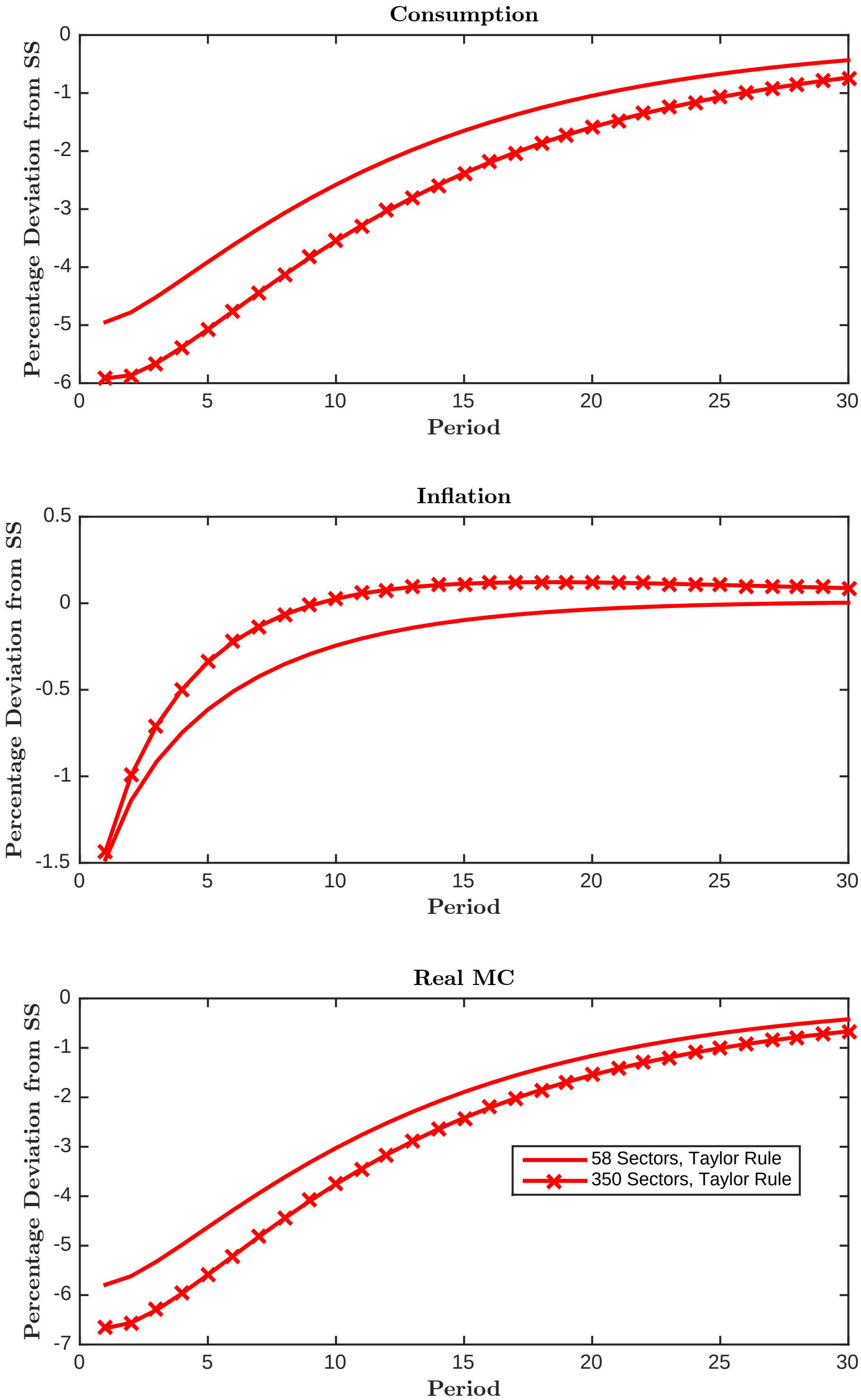
This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 350-sector model for different cases (see Table 3) for different values of structural parameters.

Figure 6: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock (exogenous nominal demand)**



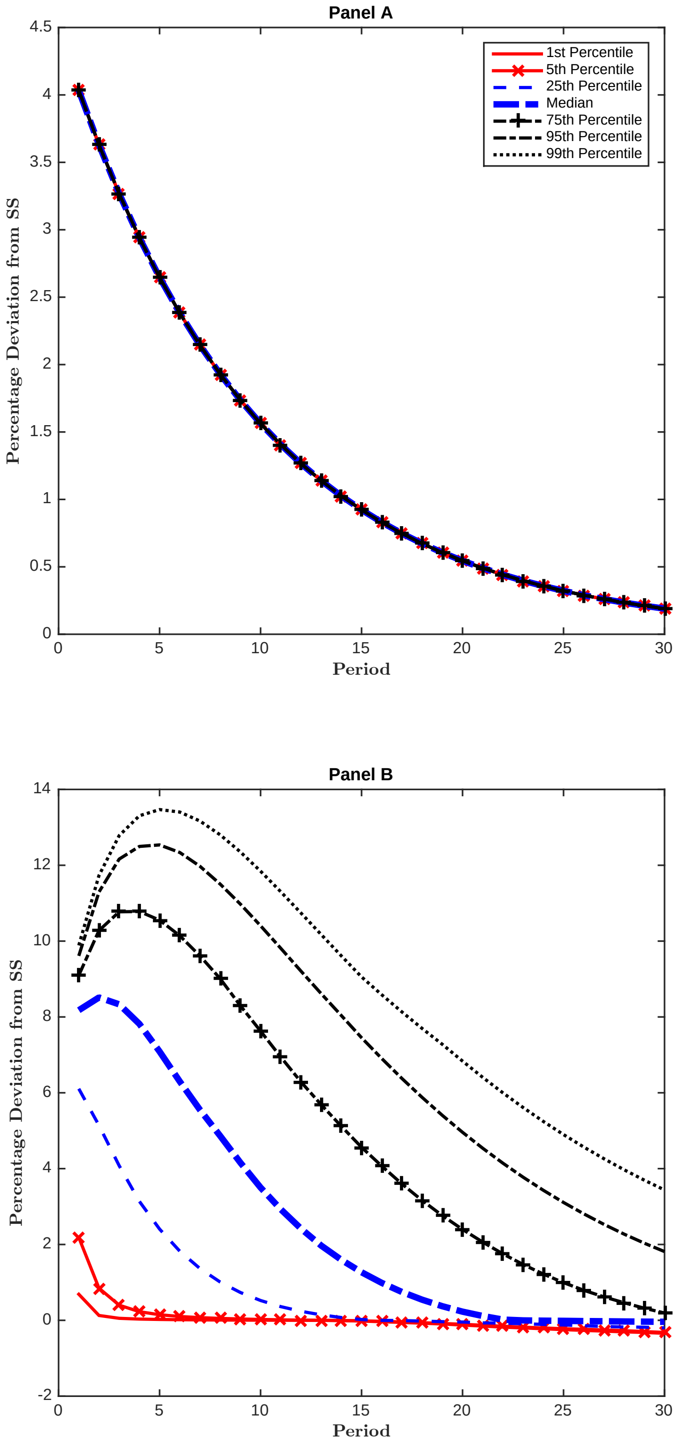
This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 350-sector model for case 6 (see Table 3), closing the model with positing exogenous nominal demand.

Figure 7: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock (58 vs 350 sector economy)**



This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 58- and 350-sector model for case 6 (see Table 3).

Figure 8: **Response of Markups to Monetary Policy Shock**



This figure plots the impulse response function of markups to a one-standard-deviation monetary policy shock for a 350-sector model for different case 2 in Panel A and case 6 in Panel B (see Table 3).

Table 1: Descriptive Statistics

The table reports the moments of the frequency of price adjustment, FPA, distribution for a 58-sector model in Panel A and a 350-sector model in Panel B.

	Mean	Median	Std	25$^{\text{th}}$ Pct	75$^{\text{th}}$ Pct
	Panel A. 58 Sector Economy				
FPA	0.19	0.14	0.16	0.08	0.25
	Panel B. 350 Sector Economy				
FPA	0.19	0.12	0.20	0.06	0.26

Table 2: Calibration Parameters

This table reports the parameter values of the calibration of the model developed in Section IV.

β	0.9975	Monthly discount factor
σ	1	Relative risk aversion
φ	2	Inverse of Frisch elasticity
δ	0.5	Average inputs share in production function
η	2	Elasticity of substitution across sectors
θ	6	Elasticity of substitution within sectors
ϕ_π	1.24	Responsiveness of monetary policy to consumption inflation
ϕ_c	0.33/12	Responsiveness of monetary policy to output variations
ρ	0.9	Persistence of shocks (equal across shocks)

Table 3: **Overview of Calibration Cases**

This table details the frequencies, consumption weights, and input-output linkages for the different cases employed in the calibration.

	Frequencies	Consumption Weights	Input-Output Linkages
Case 1	flexible	homogeneous	homogeneous
Case 2	sticky, homogeneous	homogeneous	homogeneous
Case 3	sticky, heterogeneous	homogeneous	homogeneous
Case 4	sticky, heterogeneous	heterogeneous	heterogeneous (size weights)
Case 5	sticky, heterogeneous	heterogeneous	homogeneous
Case 6	sticky, heterogeneous	heterogeneous	heterogeneous

Table 4: **Response to Monetary Policy Shock**

This table reports the impact response, the cumulative impulse response, and the persistence of the response defined as AR(1) coefficient due to a one-percent monetary policy shock for consumption (Panel A), inflation (Panel B), and real marginal costs (Panel C) for a 350-sector economy for different cases (see Table 3).

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
			Panel A. Consumption			
Impact	0.00	−3.46	−5.64	−6.24	−6.13	−5.92
Cumulative IRF	−0.03	−33.11	−68.75	−82.19	−81.09	−82.64
Persistence	0.87	0.87	0.85	0.85	0.84	0.88
			Panel B. Inflation			
Impact	−2.94	−1.64	−1.31	−1.27	−1.29	−1.43
Cumulative IRF	−28.16	−15.75	−4.74	−1.29	−2.00	−2.29
Persistence	0.87	0.87	0.87	0.87	0.87	0.89
			Panel C. Real Marginal Costs			
Impact	0.00	−4.03	−6.58	−7.16	−7.08	−7.35
Cumulative IRF	−0.03	−38.62	−80.21	−81.64	−89.62	−105.80
Persistence	0.87	0.87	0.90	0.91	0.90	0.92

Table 5: **Response to Monetary Policy Shock: Sorted by Cumulative Response**

This table reports the cumulative real consumption response to a one-percent monetary policy shock for a 350-sector economy for different cases (see Table 3). Panel A reports the response of the least responsive sectors and Panel B reports the response of the most responsive sectors. Panels C and D list the sector numbers following the BEA classification.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
	Panel A. Cumulative Consumption Response: Least Responsive					
Least responsive	−0.05	−60.69	−46.25	−49.31	−44.06	−9.73
2	−0.05	−60.69	−46.50	−49.58	−44.33	−9.74
3	−0.05	−60.69	−46.51	−49.59	−44.33	−10.37
4	−0.05	−60.69	−46.53	−49.61	−44.36	−12.88
5	−0.05	−60.69	−46.69	−49.78	−44.53	−13.68
6	−0.05	−60.69	−46.73	−49.82	−44.57	−14.14
7	−0.05	−60.69	−46.75	−49.84	−44.59	−14.56
8	−0.05	−60.69	−46.78	−49.88	−44.62	−14.74
9	−0.05	−60.69	−47.41	−50.55	−45.29	−15.68
10	−0.05	−60.69	−47.52	−50.66	−45.40	−15.74
	Panel B. Cumulative Consumption Response: Most Responsive					
Most responsive	−0.05	−60.69	−375.63	−282.25	−314.51	−353.53
2	−0.05	−60.69	−324.40	−265.21	−290.26	−328.79
3	−0.05	−60.69	−297.53	−251.78	−272.49	−305.32
4	−0.05	−60.69	−296.68	−251.31	−271.89	−304.91
5	−0.05	−60.69	−291.68	−248.54	−268.32	−301.30
6	−0.05	−60.69	−287.35	−246.09	−265.18	−296.78
7	−0.05	−60.69	−278.02	−240.61	−258.24	−288.13
8	−0.05	−60.69	−262.75	−231.17	−246.45	−274.13
9	−0.05	−60.69	−260.51	−229.74	−244.68	−274.10
10	−0.05	−60.69	−255.53	−226.51	−240.70	−270.58

continued on next page

Table 5: **Continued from Previous Page**

This table reports the cumulative real consumption response to a one-percent monetary policy shock for a 350-sector economy for different cases (see Table 3). Panel A reports the response of the least responsive sectors and Panel B reports the response of the most responsive sectors. Panels C and D list the sector numbers following the BEA classification.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
	Panel C. BEA Sector Code: Least Responsive					
Least responsive	324191	315290	311920	311920	311920	311920
2	321992	311330	315290	315290	315290	315290
3	315290	713B00	48A000	48A000	48A000	315210
4	315210	332710	332710	332710	332710	33441A
5	311920	1119B0	33441A	33441A	33441A	335120
6	311330	335120	336212	336212	336212	48A000
7	2122A0	324191	326130	326130	326130	336212
8	112120	321992	335314	335314	335314	326130
9	1119B0	311920	339950	339950	339950	339950
10	111910	315210	335120	335120	335120	333295
	Panel D. BEA Sector Code: Most Responsive					
Most responsive	326130	112120	713B00	713B00	713B00	332710
2	332710	2122A0	112120	112120	112120	713B00
3	333295	33441A	333295	333295	333295	112120
4	33441A	333295	1119B0	1119B0	1119B0	335314
5	335120	326130	324191	324191	324191	1119B0
6	335314	336212	321992	321992	321992	324191
7	336212	111910	2122A0	2122A0	2122A0	321992
8	339950	48A000	111910	111910	111910	2122A0
9	48A000	339950	311330	311330	311330	111910
10	713B00	335314	315210	315210	315210	311330

Table 6: **Response to Monetary Policy Shock** ($\phi_\pi = 2.5$)

This table reports the impact response, the cumulative impulse response, and the persistence of the response defined as AR(1) coefficient due to a one-percent monetary policy shock for consumption (Panel A), inflation (Panel B), and real marginal costs (Panel C) for a 350-sector economy for different cases (see Table 3) with a coefficient on inflation in the Taylor rule of $\phi_\pi = 2.5$.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
			Panel A. Consumption			
Impact	0.00	−1.13	−2.26	−2.76	−2.54	−2.07
Cumulative IRF	−0.01	−10.78	−42.54	−95.97	−74.00	−69.54
Persistence	0.87	0.87	0.90	0.93	0.92	0.94
			Panel B. Inflation			
Impact	−0.62	−0.54	−0.69	−0.83	−0.78	−0.76
Cumulative IRF	−5.98	−5.13	−3.91	−3.62	−3.76	−4.25
Persistence	0.87	0.87	0.92	0.94	0.94	0.94
			Panel C. Real Marginal Costs			
Impact	0.00	−1.31	−2.64	−3.11	−2.92	−2.59
Cumulative IRF	−0.01	−12.57	−49.63	−87.16	−80.32	−86.38
Persistence	0.87	0.87	0.94	0.94	0.94	0.93

Table 7: **Response to Monetary Policy Shock (variations in parameters)**

This table reports the impact response, the cumulative impulse response, and the persistence of the response defined as AR(1) coefficient due to a one-percent monetary policy shock for consumption (Panel A), inflation (Panel B), and real marginal costs (Panel C) for a 350-sector economy for different cases (see Table 3) for different values of structural parameters.

	Base	$\sigma = 2$	$\phi = 1$	$\delta = 0.7$	$\eta = 6$	$\theta = 10$	$\rho = 0.95$
				Panel A. Consumption			
Impact	−5.92	−3.70	−6.23	−6.61	−6.58	−5.76	−8.65
Cumulative IRF	−82.64	−46.81	−81.42	−79.66	−80.41	−83.13	−208.48
Persistence	0.88	0.87	0.89	0.90	0.78	0.88	0.91
				Panel B. Inflation			
Impact	−1.43	−1.14	−1.20	−0.91	−1.02	−1.54	−2.60
Cumulative IRF	−2.29	−1.61	−1.88	−1.53	−0.89	−2.59	−10.18
Persistence	0.89	0.88	0.89	0.89	0.83	0.89	0.92
				Panel C. Real Marginal Costs			
Impact	−7.35	−6.12	−5.81	−4.21	−7.98	−7.79	−10.78
Cumulative IRF	−105.80	−79.99	−81.66	−60.92	−80.91	−115.74	−262.60
Persistence	0.92	0.91	0.92	0.91	0.90	0.92	0.94

Table 8: **Response to Monetary Policy Shock (exogenous nominal demand and 58 sector economy)**

This table reports the impact response, the cumulative impulse response, and the persistence of the response defined as AR(1) coefficient due to a one-percent monetary policy shock for consumption (Panel A), inflation (Panel B), and real marginal costs (Panel C) for a 350-sector economy with Taylor Rule, exogenous nominal demand, and a 58-sector economy with Taylor Rule for case 6 (see Table 3).

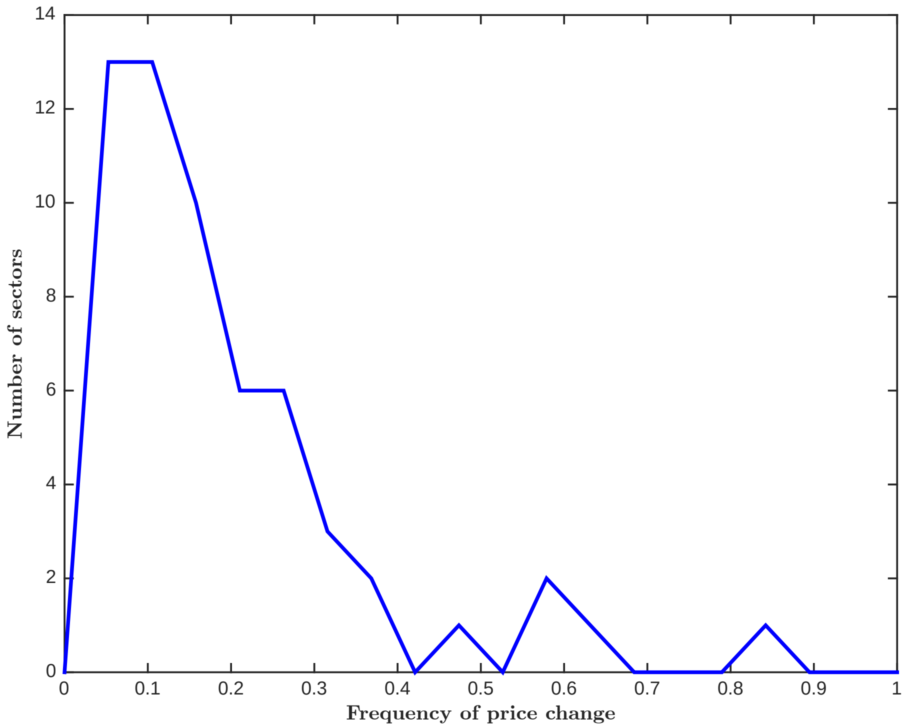
	350 Sectors Taylor Rule	350 Sectors Exogenous Demand	58 Sectors Taylor Rule
		Panel A. Consumption	
Impact	−5.92	−0.86	−4.49
Cumulative IRF	−82.64	−5.01	−55.18
Persistence	0.88	0.76	0.90
		Panel B. Inflation	
Impact	−1.43	−0.14	−1.65
Cumulative IRF	−2.29	−0.05	−9.39
Persistence	0.89	0.77	0.78
		Panel C. Real Marginal Costs	
Impact	−7.35	−1.05	−5.46
Cumulative IRF	−105.80	−6.46	−71.80
Persistence	0.92	0.82	0.91

Online Appendix: Production Networks and the Propagation of Monetary Policy Shocks

Ernesto Pasten, Raphael Schoenle, and Michael Weber

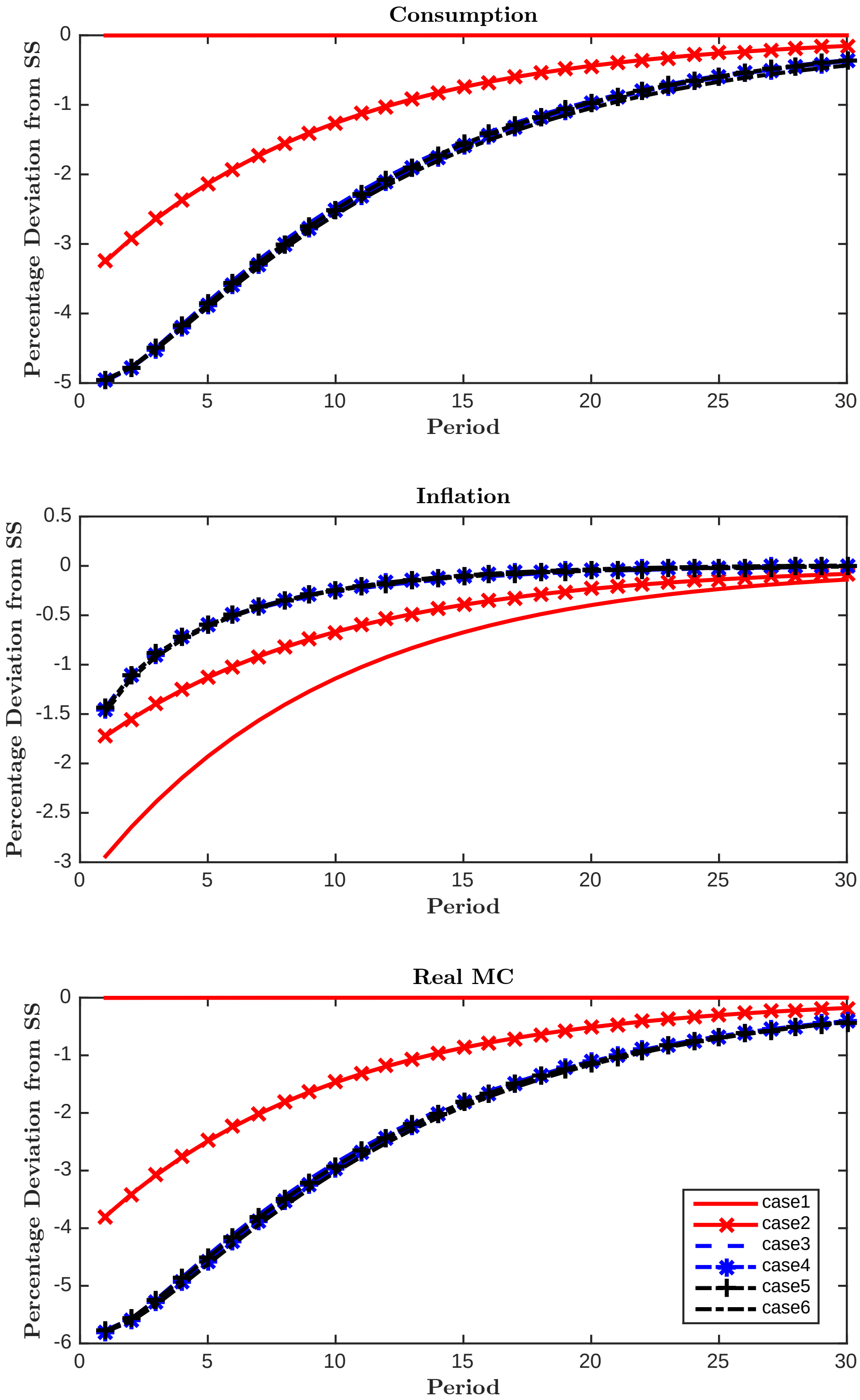
Not for Publication

Figure A.1: **Distribution of the Frequency of Price Adjustment (58 Sectors)**



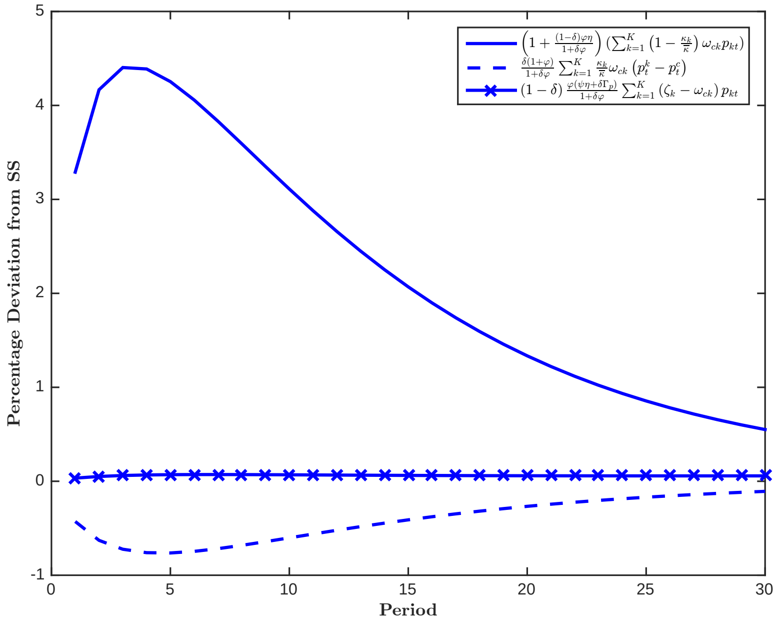
This figure plots the distribution of the frequency of price adjustment for a 58-sector model.

Figure A.2: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock (58 Sectors)**



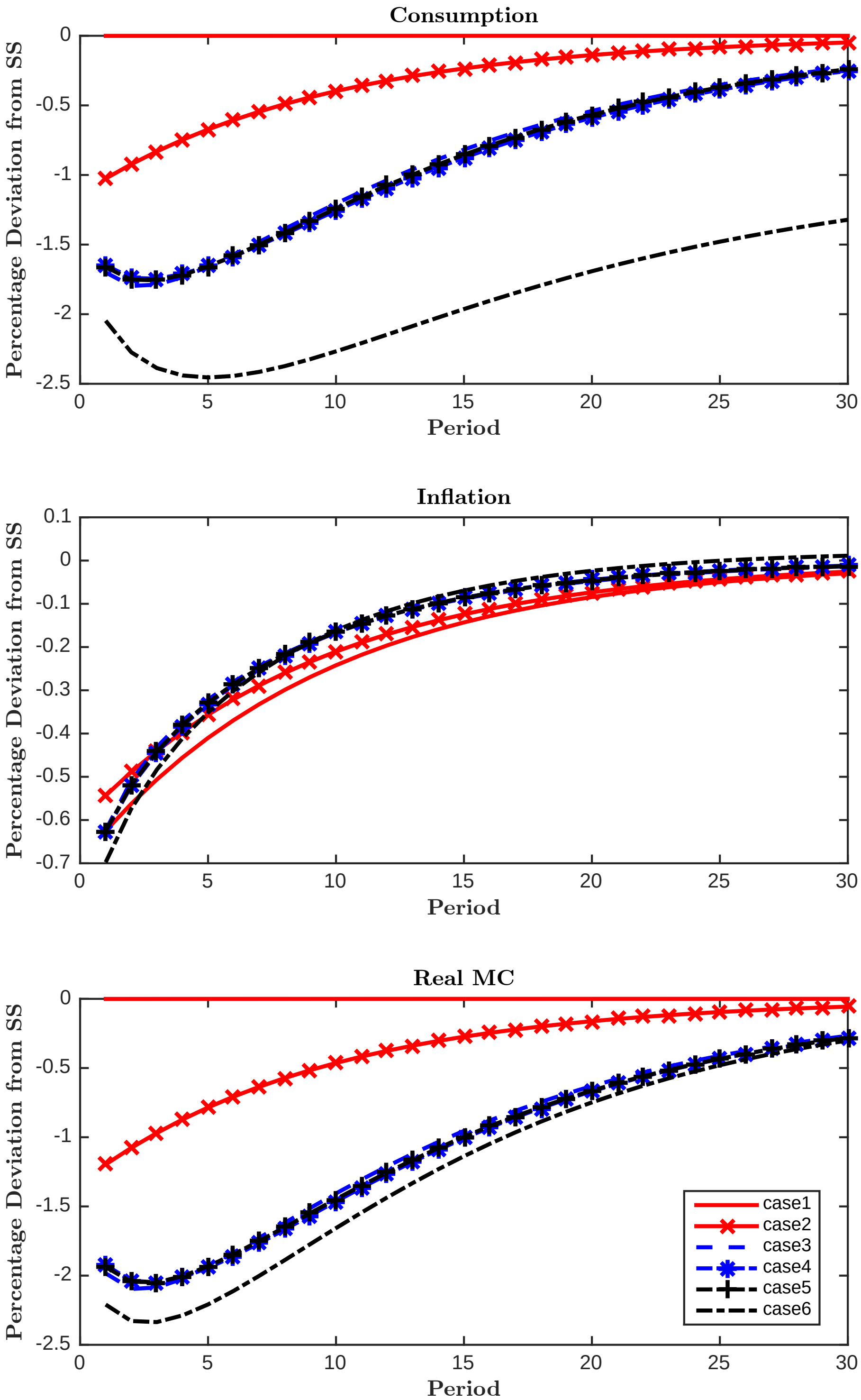
This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard deviation monetary policy shock for a 58-sector model for different cases (see Table 3).

Figure A.3: **Decomposition of the Overall Response of Markups into Components (58 Sectors)**



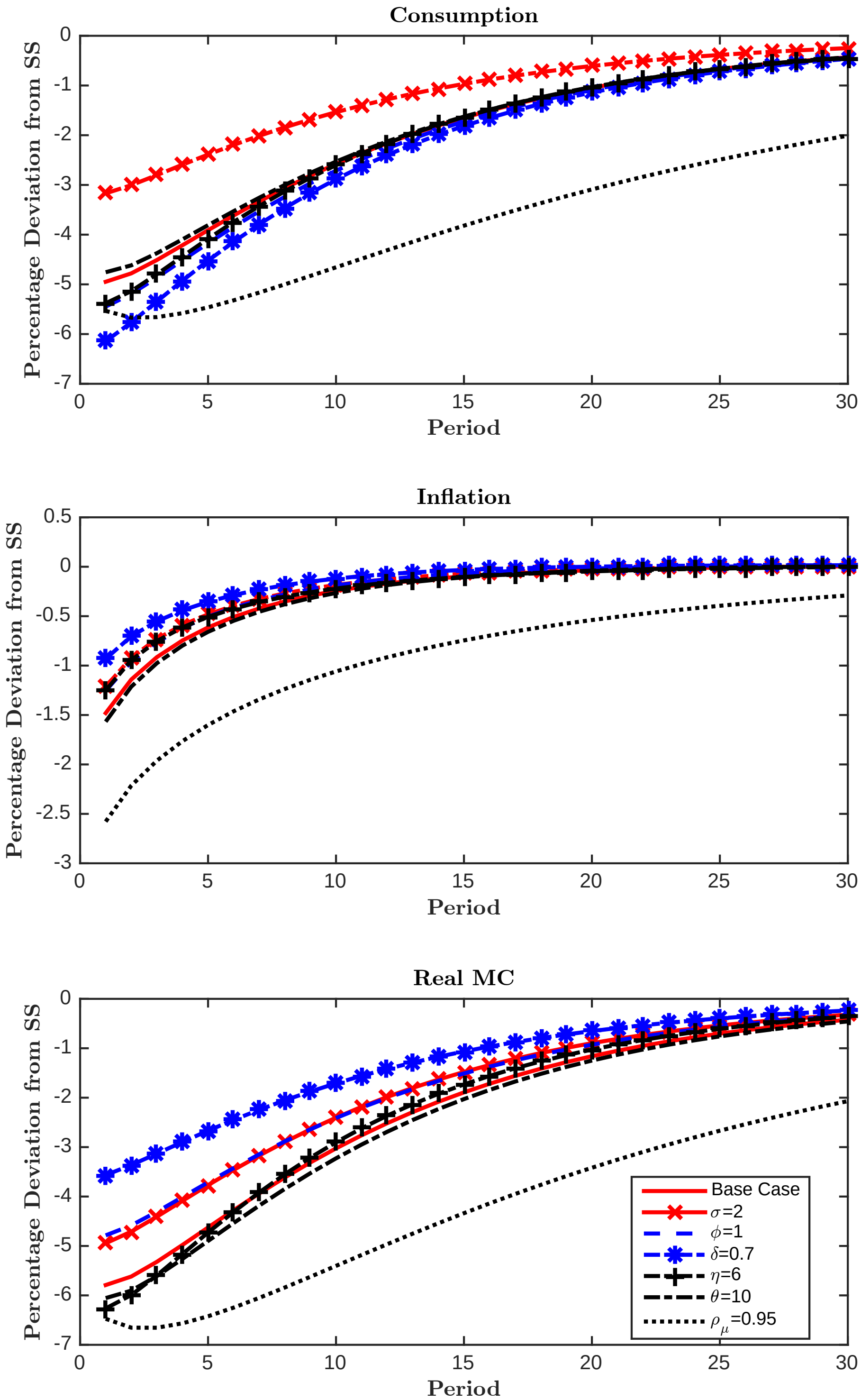
This figure decomposes the overall response of consumption to a one-standard-deviation monetary policy shock for a 58-sector model into the three different components discussed in Section IV.

Figure A.4: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock (58 Sectors, $\phi_\pi = 2.5$)**



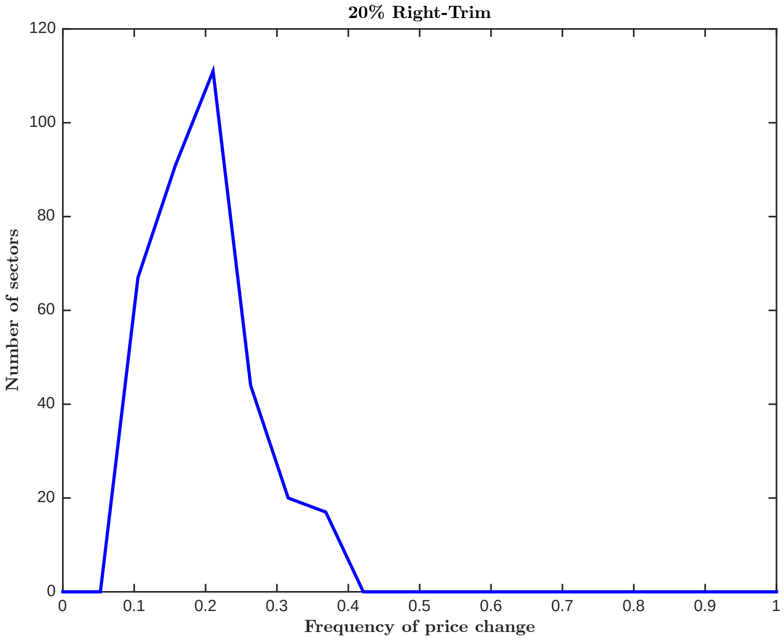
This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 58-sector model for different cases (see Table 3) with a coefficient on inflation in the Taylor rule of $\phi_\pi = 2.5$.

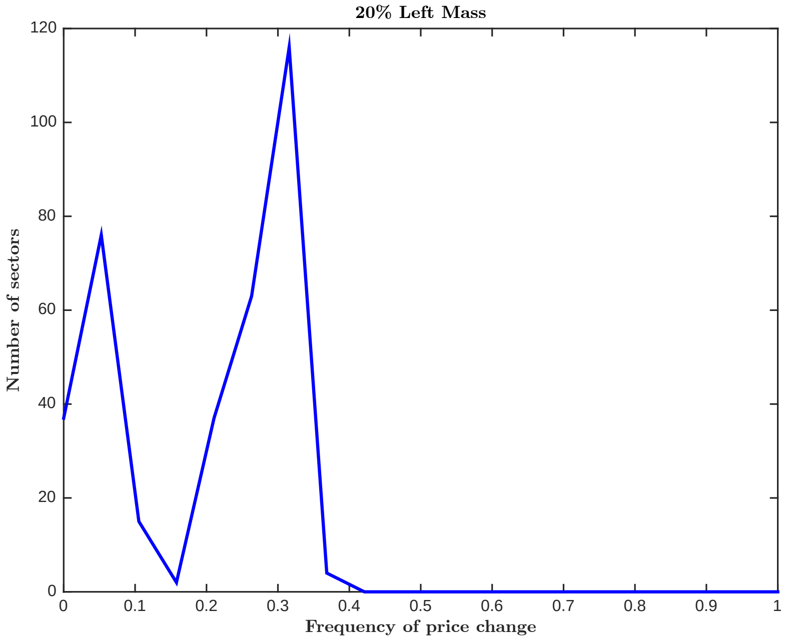
Figure A.5: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock (58 Sectors, Variations in parameters)**



This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 58-sector model for different cases (see Table 3) for different values of structural parameters.

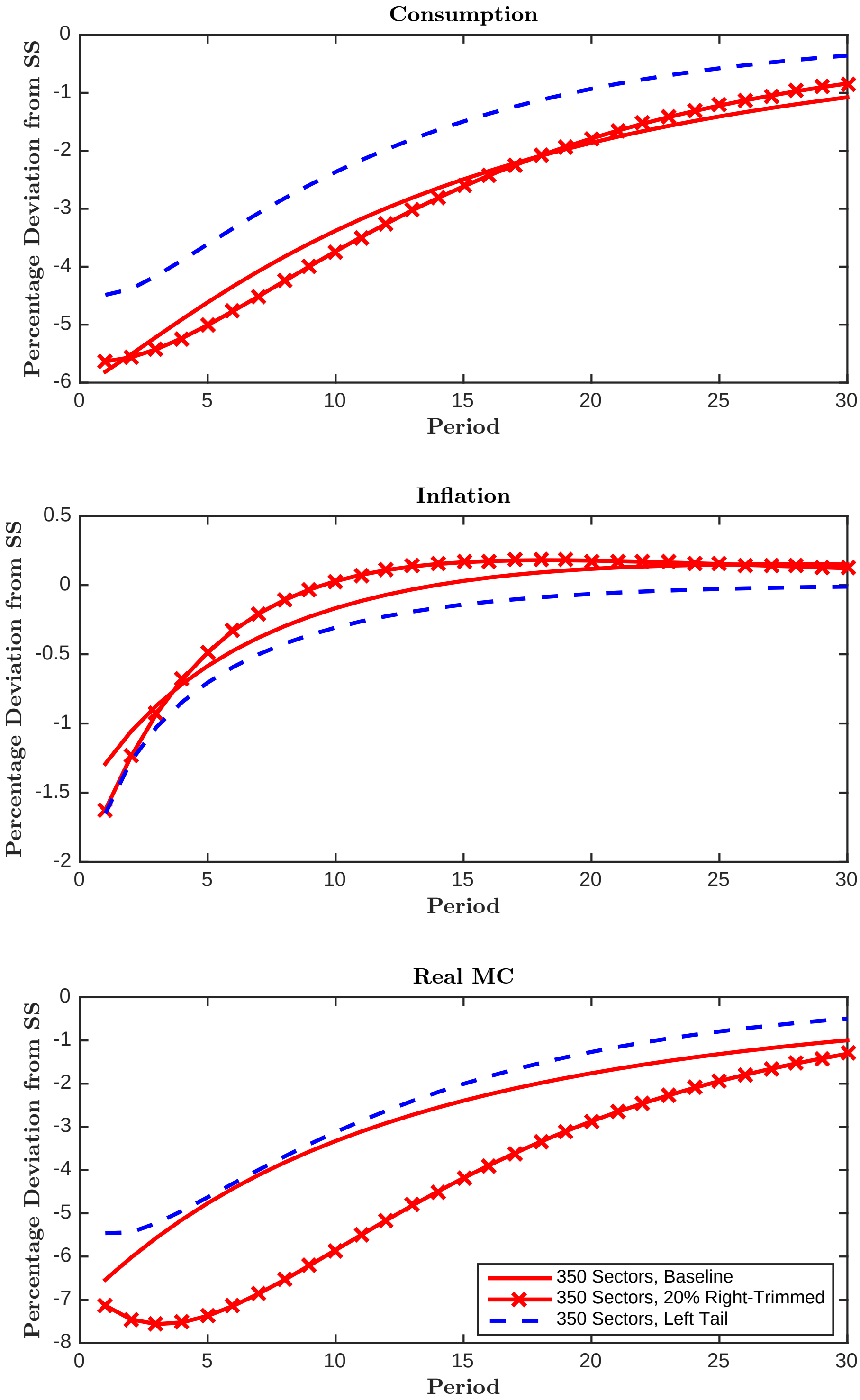
Figure A.6: **Trimmed Distribution of the Frequency of Price Adjustment**





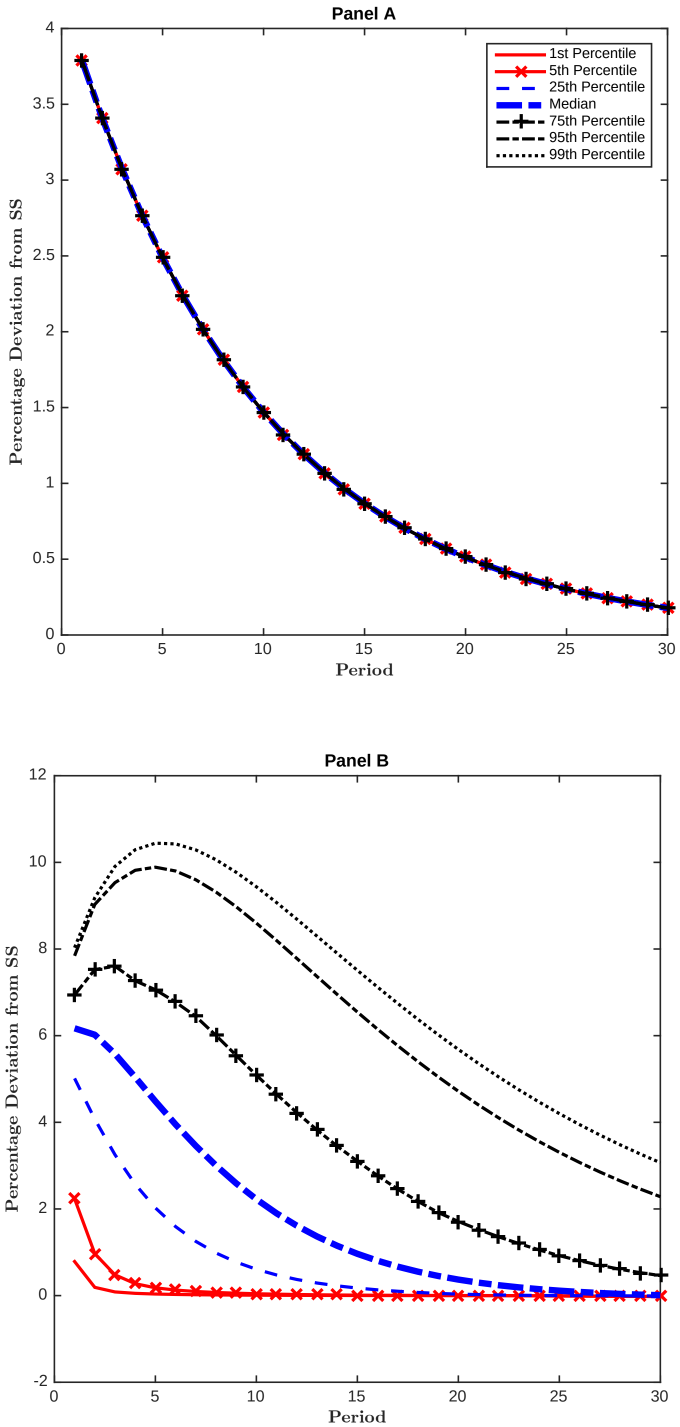
This figure plots the distribution of the frequency of price adjustment for a 350-sector model. The top panel trims the 20% stickiest sectors, whereas the bottom panel generates a heavy left tail.

Figure A.7: **Response of Real Consumption, Inflation, and Real Marginal Costs to Monetary Policy Shock: Trimmed Tail**



This figure plots the impulse response function of real consumption, inflation, and real marginal costs to a one-standard-deviation monetary policy shock for a 350-sector model for case 6 (see Table 3) for trimmed distributions of the frequency of price adjustment.

Figure A.8: **Response of Markups to Monetary Policy Shock (58 Sectors)**



This figure plots the impulse response function of markups to a one-standard-deviation monetary policy shock for a 58-sector model for different case 2 in Panel A and case 6 in Panel B (see Table 3).

Table A.1: **Response to Monetary Policy Shock: Sorted by Cumulative Response**

This table reports the cumulative real consumption response to a one-percent monetary policy shock for a 58-sector economy for different cases (see Table 3). Panel A reports the response of the least responsive sectors and Panel B reports the response of the most responsive sectors. Panels C and D list the sector numbers following the BEA classification.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
	Panel A. Cumulative Consumption Response: Least Responsive					
Least responsive	−0.05	−51.10	−39.57	−38.71	−40.51	−22.79
2	−0.05	−51.10	−41.92	−41.08	−42.85	−24.46
3	−0.05	−51.10	−42.85	−42.02	−43.79	−24.51
4	−0.05	−51.10	−42.93	−42.11	−43.87	−25.89
5	−0.05	−51.10	−44.91	−44.14	−45.87	−29.48
6	−0.05	−51.10	−48.68	−48.03	−49.68	−34.87
7	−0.05	−51.10	−50.38	−49.80	−51.42	−36.63
8	−0.05	−51.10	−52.94	−52.47	−54.02	−37.47
9	−0.05	−51.10	−55.45	−55.10	−56.59	−39.59
10	−0.05	−51.10	−56.03	−55.71	−57.19	−50.30
	Panel B. Cumulative Consumption Response: Most Responsive					
Most responsive	−0.05	−51.10	−245.19	−259.22	−253.78	−269.79
2	−0.05	−51.10	−239.51	−253.08	−247.86	−261.32
3	−0.05	−51.10	−227.84	−240.45	−235.68	−249.38
4	−0.05	−51.10	−210.89	−222.12	−218.01	−227.49
5	−0.05	−51.10	−189.72	−199.24	−195.95	−212.71
6	−0.05	−51.10	−184.21	−193.28	−190.20	−207.28
7	−0.05	−51.10	−183.44	−192.44	−189.40	−200.50
8	−0.05	−51.10	−180.88	−189.68	−186.73	−196.79
9	−0.05	−51.10	−173.49	−181.70	−179.03	−190.32
10	−0.05	−51.10	−165.74	−173.33	−170.96	−179.01

continued on next page

Table A.1: **Continued from Previous Page**

This table reports the cumulative real consumption response to a one-percent monetary policy shock for a 58-sector economy for different cases (see Table 3). Panel A reports the response of the least responsive sectors and Panel B reports the response of the most responsive sectors. Panels C and D list the sector numbers following the BEA classification.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
	Panel C. BEA Sector Code: Least Responsive					
Least responsive	324	321	452	452	452	323
2	323	339	5411	5411	5411	521CI
3	339	493	493	493	493	452
4	3364OT	713	3364OT	3364OT	3364OT	22
5	333	486	713	713	713	493
6	321	211	22	22	22	3364OT
7	23	42	339	339	339	486
8	22	212	486	486	486	333
9	212	621	333	333	333	5411
10	211	324	321	321	321	321
	Panel D. BEA Sector Code: Most Responsive					
Most responsive	42	61	323	323	323	212
2	452	22	621	621	621	339
3	486	23	521CI	521CI	521CI	621
4	493	3364OT	42	42	42	211
5	521CI	21CI	211	211	211	81
6	5411	323	81	81	81	61
7	61	452	212	212	212	713
8	621	81	324	324	324	324
9	713	333	23	23	23	23
10	81	5411	61	61	61	42