Monetary Policy and Production Networks: An Empirical Investigation *

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Abstract

The ability of input-output linkages across economic sectors to amplify the effects of monetary policy shocks has received a large amount of attention in theoretical literature on strategic complementarities in price setting. In contrast, empirical evidence on such role of production networks remains almost non-existent. This paper is the first study in the literature to econometrically assess the contribution of production networks to the effect of monetary policy shocks on real macroeconomic variables. In particular, we estimate that 20 to 45 per cent of the effect of monetary policy shocks on US consumption comes from the amplification through input-output linkages. The effect of production networks is also observed to come with a delay of around 18 months. Our results survive a number of robustness checks, including the level of sectoral aggregation and the way in which monetary policy shocks are identified.

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1 Introduction and literature review

How different economic sectors are interlinked and affect each other has long been a question of interest to economists – at least since Wassily Leontief's invention of input-output analysis in the 1950s. Nevertheless, it is only in recent years that input-output linkages, or production networks, have firmly established their presence in neoclassical macroeconomics. Indeed, production networks have recently shed light on a range of fundamental economic questions, such as the origin of business cycles and reasons behind money non-neutrality.

Most notably, Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012) build on the multi-sector framework of Long and Plosser (1983), and theoretically show that when certain sectors are disproportionally large suppliers of inputs to the rest of the economy, sectoral shocks can get amplified by input-output linkages, causing aggregate fluctuations. Both the importance of sector-specific shocks for aggregate fluctuations and the ability of production networks to amplify the effect of those shocks have found support in the empirical literature (Foerster, Sarte and Watson, 2011; Acemoglu, Akcigit and Kerr, 2015).

On the side of aggregate nominal shocks, Basu (1995) theoretically establishes that monetary policy shocks get amplified in presence of production networks, as the latter create strategic complementarities in firms' price setting. Intuitively, following a monetary policy shock, firms might delay their price adjustment over and above their own price stickiness due to the fact that the prices of their inputs, set by their potentially stickier suppliers, might have not been adjusted yet. The latter can add persistence to the marginal cost and hence make firms inherit stickiness from their suppliers, thus creating extra short-run money non-neutrality. The above mechanism has since received a large amount of attention in theoretical literature (Nakamura and Steinsson, 2010; Pasten, Schoenle and Weber, 2016).

However, empirical evidence on the ability of production networks to amplify the effects of monetary policy shocks on the real economy remains almost non-existent. In what follows we make a first step towards filling this large gap in the literature.

1.1 Contribution

Our paper is the first study to offer econometric evidence on the role of production networks in the effect of monetary policy shocks on real macroeconomic variables. In particular, we estimate that 20 to 45 per cent of the effect of monetary policy shocks on US consumption is due to production networks. Another finding is that the contribution of production networks comes in with a lag of around 18 months.

In order to obtain our results, we construct a dataset on final consumption for up to 231 sectors of the US economy and apply it to an econometric specification guided by results from a multi-sector New Keynesian model with roundabout production and sector-specific frequencies of price adjustment. Our empirical results also contribute to the literature on sector-level impulse responses to aggregate shocks, with our theoretical framework delivering new insights on reconciling the observed response patterns.

In addition, both our empirical results and the theoretical framework built around it generate a number of testable hypotheses for future research, particularly regarding the reasons behind heterogeneous responses of economic sectors to monetary policy shocks.

1.2 Literature review

Our results should be viewed in the context of at least two strands of existing literature.

Firstly, we contribute to the relatively recent empirical literature that focuses on the extent to which production networks amplify the effects of economic shocks. On the side of sector-specific shocks, Acemoglu, Akcigit and Kerr (2015) identify sector-specific fiscal, imports and productivity shocks and show that the vast majority of their non-negligible impact on US sectoral value added comes from the amplification via input-output linkages. Barrot and Sauvagnat (2016) identify even more disaggregated firm-level shocks via the occurrence of natural disasters and similarly report large spillovers from suppliers of inputs to their customers. The empirical literature on amplification of aggregate nominal shocks remains extremely thin. One exception is Ozdagli and Weber (2016) who use spatial econometric techniques to show that 50 to 85 per cent of the effect of monetary policy shocks on US stock returns comes from the amplification through production networks. However, they build their intuition in the flexible-price framework of Long and Plosser (1983) and do not estimate amplification coming specifically from strategic complementarities in price setting.

Secondly, our results represent a valuable empirical addition to the predominantly theoretical literature on complementarities in price setting created by production networks. Following the seminal study by Basu (1995), Carvalho (2006) shows in a DSGE setting that when the degree of price stickiness is allowed to vary across sectors, complementarities in price setting significantly increase the degree of money non-neutrality. Nakamura and Steinsson (2010) develop a multi-sector menu cost model that they calibrate for up to 14 US sectors and report large increases in short-run money non-neutrality coming from differential price stickiness across sectors coupled with intermediate inputs. Pasten, Schoenle and Weber (2016) develop a multi-sector model with sector-specific probabilities of price adjustment that they calibrate to 350 sectors of the US economy and confirm large amplifications of monetary policy shocks coming from strategic complementarities in price setting.

Several recent studies have used a mixture of aggregate and sectoral data to explicitly estimate multi-sector New Keynesian models with roundabout production and heterogeneous price stickiness. Most notably, Carvalho and Lee (2011) estimate sector-specific probabilities of price adjustment for 15 major sectors of the US economy, by matching model-implied responses of sectoral prices to their empirical counterparts reported in Boivin, Giannoni and Mihov (2009). More recently, Bouakez, Cardia and Ruge-Murcia (2014) estimate a 30-sector menu cost model with roundabout production, and show that the implied sectoral frequencies of price adjustment match those from micro-based studies (Nakamura and Steinsson, 2008).

1.3 Structure

The rest of the paper is structured as follows. In Section 2 we build a theoretical framework and derive an expression for sectoral consumption that motivates our eventual econometric analysis. Section 3 outlines the construction of our dataset.

Our econometric strategy is detailed in Section 4. Section 5 discusses the main empirical results of this paper, whose robustness is then tested in Section 6. Section 7 addresses some of the discrepancies between our empirical results and our theoretical framework and in doing so suggests several direction for further research. Section 8 concludes and outlines our strategy for future work.

2 Model

In this section, we formalise our ideas in the context of a multi-sector sticky-price New Keynesian model with roundabout production and sector-specific Calvo parameters, most closely related to the models studied in Carvalho and Lee (2011) and Pasten, Schoenle and Weber (2016). Our main goal here is twofold. Firstly, we would like to build intuition regarding the channels through which production networks create complementarities in firms' price setting and thus greater short-run money non-neutrality that leads to a larger effect of monetary policy on real economic variables. Secondly, we consider a simplified version of our model with myopic firms that allows us to find analytical solution for sectoral consumption. The latter motivates our econometric specification.

2.1 Firms

On the production side, our economy consists of K sectors, indexed by $k \in \{1, 2, ..., K\}$, and a continuum of monopolistically competitive firms, indexed by $j \in [0, 1]$, that each belongs to one sector. Denoting by Φ_k the set of all firms in sector k, its corresponding measure is given by f_k, so that $\sum_{k=1}^{K} f_k = 1$. The production function of firm j that operates in sector k is given by:

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

where Y_{kjt}, L_{kjt} and Z_{kjt} are, respectively, total output, labour input and intermediate inputs of firm j in sector k at time t, and δ is the share of intermediate inputs that is assumed to be common for all firms across all sectors.[1] Total intermediate inputs used is an aggregator for intermediate goods purchased from all the different

[1] See Shamloo (2010) for a similar model with sector-specific shares of intermediate inputs.

sectors in the economy, so that:

$$Z_{kjt} \equiv \prod_{r=1}^{K} \omega_{kr}^{-\omega_{kr}} Z_{kjt}^{\omega_{kr}}(r), \tag{2}$$

where $Z_{kjt}(r)$ is the intermediate inputs purchased by firm j in sector k from all firms in sector r; ω_{kr} is the relative intensity with which firms in sector r use goods produced in sector r as inputs, so that $\sum_{r=1}^{K} \omega_{kr} = 1 \quad \forall k$. Note that the above aggregation implies unit elasticity of substitution between inputs from different sectors. In turn, $Z_{kjt}(r)$ is also an aggregator for all the inputs purchased from the different firms that belong to sector r, namely:

$$Z_{kjt}(r) \equiv \left(f_r^{-\frac{1}{\theta}} \int_{\Phi_r} Z_{kjt}(r, j')^{\frac{\theta-1}{\theta}} dj' \right)^{\frac{\theta}{\theta-1}}, \tag{3}$$

where $Z_{kjt}(r, j')$ denotes total inputs purchased by firm j in sector k from firm j' in sector r. The above aggregator implies elasticity of substitution between inputs from firms that belong to the same sector equal to θ. We assume $\theta > 1$ in order to account for that fact that it is harder to substitute inputs across sectors than within a particular sector.

Given the choice of Z_{kjt}, the firm optimally chooses $\{Z_{kjt}(r)\}_{r=1}^{K}$ so that the overall cost of assembling such basket, given the aggregator in (2), is minimised. Hence, in equilibrium:

$$Z_{kjt}(r) = \omega_{kr} \left(\frac{P_{rt}}{P_t^k} \right)^{-1} Z_{kjt}, \tag{4}$$

where P_{rt} is a sectoral price index for sector r, P_t^k is the sector-specific inputs price index for sector k (both defined below). Note that (4) clarifies the meaning of ω_{kr}, namely, in equilibrium, for any firm in sector k it is the proportion of its total expenditure on intermediate inputs ($P_t^k Z_{ktj}$) spent on intermediate inputs produced in sector r ($P_{rt} Z_{kjt}(r)$). Thus, for the US, ω_{kr} corresponds to the (k, r) entry of an input-output matrix published by the Bureau of Economic Analysis. Similarly, given its choice of $Z_{kjt}(r)$, the firm optimally chooses $\{Z_{kjt}(r, j')\}_{j' \in \Phi_r}$, subject to the aggregator in (3), yielding:

$$Z_{kjt}(r, j') = \frac{1}{f_r} \left(\frac{P_{rj't}}{P_{rt}} \right)^{-\theta} Z_{kjt}(r), \tag{5}$$

where $P_{rj't}$ is the price set by firm j' in sector r. Finally, sectoral and inputs price indices used above are given by:

$$P_t^k = \prod_{r=1}^{K} P_{rt}^{\omega_{kr}}, \tag{6}$$

and

$$P_{rt} = \left(\frac{1}{f_r} \int_{\Phi_r} P_{ri't}^{1-\theta} dj' \right)^{\frac{1}{1-\theta}}. \tag{7}$$

We assume an economy-wide labour market with firms in all sectors facing the same wage W_t [2]; given that and the inputs price index P_t^k the firm wishes to choose L_{kjt} and Z_{kjt} in order to minimise its total inputs cost subject to the production function in (1). The latter delivers the following expression for the optimal labour/intermediate inputs mix:

$$\frac{Z_{kjt}}{L_{kjt}} = \frac{\delta}{1-\delta} \frac{W_t}{P_t^k}; \tag{8}$$

and for the nominal marginal cost:

$$MC_{kjt} = \frac{\delta^{-\delta}}{(1-\delta)^{1-\delta}} W_t^{1-\delta} (P_t^k)^{\delta}. \tag{9}$$

Two things are worth noting about the nominal marginal cost in (9). Firstly, the right hand side of the expression lacks any j subscripts, implying that the nominal marginal cost is the same for all firms within a particular sector. Therefore, from now we drop the j subscript from the marginal cost. Secondly, one can see that the marginal cost for any firm is effectively a weighted average of its labour input cost, given by the wage, and its sector-specific inputs price index, whose relative importance increases in the share of intermediate inputs δ. Indeed, when $\delta = 0$, we get that $MC_{kt}^{\delta=0} = W_t$, which is standard result from a New Keynesian model with constant returns to scale production and no intermediate inputs. One can already see how $\delta > 0$ makes the marginal cost of any firm sensitive to prices set by its suppliers. As we will see later, this is the key mechanism that makes prices set in our economy strategic complements.

Price stickiness in our economy is modelled as in Calvo (1983), although the probability of price adjustment is allowed to vary across sectors. More precisely, in

[2] Allowing for sector-specific or even firm-specific labour markets is another mechanism that can create strategic complementarities is price setting, as discussed in Carvalho and Lee (2011). In this paper, we would like to restrict our focus to the role of production networks, and hence we make it the only source of strategic complementarities in price setting.

any period a firm in sector k has probability $(1-\alpha_k)$ of setting its price equal to its optimal value. The optimal price at time t is chosen to maximise expected future discounted nominal profits:

$$\max_{P_{kjt}} \mathbb{E}_t \sum_{s=0}^{\infty} \alpha_k^s F_{t,t+s}(P_{kjt}Y_{kj,t+s} - W_{t+s}L_{kj,t+s} - P_{t+s}^k Z_{kj,t+s}), \tag{10}$$

subject to the production function in (1); $F_{t,t+s}$ is the stochastic discount factor between periods t and $t+s$ and is defined in the next subsection. After imposing the optimal inputs mix condition from (8) and the marginal cost equation from (9), the first order condition for the optimal price for any firm in sector k, P_{kt}^* is given by:

$$P_{kt}^* = \frac{\theta}{\theta-1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \alpha_k^s F_{t,t+s} Y_{kj,t+s} MC_{k,t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} \alpha_k^s F_{t,t+s} Y_{kj,t+s}}. \tag{11}$$

Given that the optimal price is identical for all firms within a sector, sectoral price index can be obtained by simple aggregation using (7):

$$P_{kt} = \left[\alpha_k P_{k,t-1}^{1-\theta} + (1-\alpha_k)(P_{kt}^*)^{1-\theta}\right]^{\frac{1}{1-\theta}}. \tag{12}$$

2.2 Households

A continuum of infinitely lived households populates our economy and owns all the firms. Markets are assumed to be complete, so a full set of Arrow-Debreu securities is available. The representative households makes choices to maximise the lifetime utility:

$$\max_{\{C_t, L_t, B_{t+1}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \gamma L_t\right) \tag{13}$$

subject to

$$P_t^c C_t + \mathbb{E}_t\left[F_{t,t+1}B_{t+1}\right] \leq B_t + W_t L_t + \sum_{k=1}^{K} \Pi_{kt}, \tag{14}$$

where C_t and P_t^c are the composite consumption good and the consumption price index (defined below) respectively, L_t is labour supply, B_{t+1} is the stochastic payoff of securities purchased at time t, $F_{t,t+1}$ is the stochastic discount factor to price those securities at time t and Π_{kt} denotes aggregate nominal profits of firms in sector k; β is the discount factor for future utility and γ is a parameter capturing the relative disutility of labour. The utility is assumed to be linear in labour, following the indivisible labour model introduced by Hansen (1985).

The composite consumption index C_t is an aggregator for the final consumption of goods produced in the different sectors of our economy, and, just like for intermediate inputs, we assume unit elasticity of substitution across sectors:

$$C_t \equiv \prod_{k=1}^{K} \omega_{ck}^{-\omega_{ck}} C_{kt}^{\omega_{ck}}, \tag{15}$$

where ω_{ck} is the relative weight consumers put on goods produced in sector k, so that $\sum_{k=1}^{K} \omega_{ck} = 1$; C_{kt} is in turn an aggregator for the final consumption of goods produced by firms that belong to sector k:

$$C_{kt} \equiv \left(f_r^{-\frac{1}{\theta}} \int_{\Phi_r} C_{kj't}^{\frac{\theta-1}{\theta}} dj' \right)^{\frac{\theta}{\theta-1}}. \tag{16}$$

Note that our earlier requirement that $\theta > 1$ now implies that it is harder to substitute consumption of goods from different sectors than substitute goods within the same sector which is entirely plausible.

The maximisation problem in (13)-(14) delivers standard first-order conditions, namely an equation for the stochastic discount factor

$$F_{t,t+s} = \beta^s \left(\frac{C_{t+s}}{C_t} \right)^{-1} \frac{P_t^c}{P_{t+s}^c}, \tag{17}$$

and an equation for consumption-labour supply choice:

$$C_t^{-1} = \gamma \frac{P_t^c}{W_t}. \tag{18}$$

For a given choice of C_t, the representative household chooses a basket of sectoral consumptions $\{C_{kt}\}_{k=1}^{K}$ such the the cost of assembling this basket, given the aggregator in (15), is minimised. As a result, in equilibrium:

$$C_{kt} = \omega_{ck} \left(\frac{P_{kt}}{P_t^c} \right)^{-1} C_t, \tag{19}$$

and ω_{ck} is the proportion of total consumption expenditure ($P_t^c C_t$) spent on goods produced by firms in sector $k(P_{kt}C_{kt})$. Similarly, given C_{kt}, the representative household chooses $\{C_{kj't}\}_{j' \in \Phi_k}$ to be purchased from firms in sector k such that the total purchasing cost is minimised, given the aggregator in (16):

$$C_{kjt} = \frac{1}{f_k} \left(\frac{P_{kjt}}{P_{kt}} \right)^{-\theta} C_{kt}. \tag{20}$$

Finally, the consumption price index that satisfies $P_t^c C_t = \sum_{k=1}^{K} P_{kt} C_{kt}$ is given by:

$$P_t^c = \prod_{k=1}^{K} P_{kt}^{\omega_{ck}}. \tag{21}$$

2.3 Monetary policy

Following Nakamura and Steinsson (2010), we assume that the monetary authority acts in a way that ensures that nominal GDP, given by $S_t \equiv P_t^c C_t$, follows a random walk in logs:

$$\log S_t = \log S_{t-1} + r_t, \tag{22}$$

where $r_t = \rho_r r_{t-1} + \varepsilon_t$ defines an AR(1) process for monetary policy shocks, and innovations $\{\varepsilon_t\}_t$ constitute a zero-mean white noise process with variance σ_ε^2. The above can be rationalised by imposing a cash-in-advance constraint on aggregate final consumption, and assuming a constant velocity of money. The above assumptions imply a one-to-one positive mapping between nominal GDP and money supply, allowing us to be referring to nominal GDP and money supply interchangeably, as they are effectively represented by the same exogenous process S_t in our model. Indeed, as discussed in Nakamura and Steinsson (2013), under our assumptions the process in (22) is equivalent to a rule for money supply.

An alternative approach would be to close our model with a Taylor rule for the nominal interest rate, as done in, for example, Carvalho and Lee (2011) and Pasten et al. (2016). In the Appendix we consider the implications of such alternative monetary policy specification. All in all, none of the intuition that motivates our eventual econometric analysis is affected in any significant way.

2.4 Market clearing

In addition to the optimality conditions, budget constraints and the policy rule above, equilibrium in our economy is also characterised by the following market-clearing conditions:

$$B_t = 0, \tag{23}$$

$$L_t = \sum_{k=1}^{K} \int_{\Phi_k} L_{kjt} dj, \tag{24}$$

$$Y_{kjt} = C_{kjt} + \sum_{r=1}^{K} \int_{\Phi_r} Z_{rj't}(k,j) dj', \quad \forall k, j \tag{25}$$

where (23) represents market clearing in the securities market and stems from the fact that our securities are in zero net-supply; (24) is market clearing in the labour market indicating the equality of total labour supply of the households and total labour demand coming from all firms in all sectors; (25) represents equilibrium in goods market for each individual firm, so that total output of every firm in used either for final consumption or as intermediate inputs by other firms.

2.5 Log-linearised equilibrium

We log-linearise the equilibrium conditions from the previous subsections around a symmetric zero-inflation steady-state (which we solve for in the Appendix), thus obtaining the following system in terms of economic variables of interest (lower case letters denote log-deviations from the steady state):

$$p_{kt} = \alpha_k p_{k,t-1} + (1-\alpha_k) p^*_{kt}, \qquad k = 1, 2, ..., K \tag{26}$$

$$p^*_{kt} = (1-\beta\alpha_k) \sum_{j=0}^{\infty} (\beta\alpha_k)^j \mathbb{E}_t mc_{k,t+j}, \qquad k = 1, 2, ..., K \tag{27}$$

$$mc_{kt} = (1-\delta) w_t + \delta \sum_{r=1}^{K} \omega_{kr} p_{rt}, \qquad k = 1, 2, ..., K \tag{28}$$

$$p^c_t + c_t = w_t, \tag{29}$$

$$p^c_t + c_t = s_t, \tag{30}$$

$$c_{kt} = -p_{kt} + p^c_t + c_t, \qquad k = 1, 2, ..., K \tag{31}$$

$$c_t = \sum_{k=1}^{K} \omega_{ck} c_{kt}, \tag{32}$$

$$s_t = s_{t-1} + r_t, \quad r_t = \rho_r r_{t-1} + \varepsilon_t, \quad \{\varepsilon_t\}_t \sim i.i.d.(0, \sigma^2_\varepsilon). \tag{33}$$

Let us now have a closer look at the log-linearised equilibrium conditions. From (26) one can see that the sectoral price is a weighted average of last period's sectoral price (accounting for the proportion α_k of firms that failed to adjust their prices) and the optimal sectoral price in the current period (driven by the $(1-\alpha_k)$ share of firms who managed to adjust to the optimal price that is common to all firms within a sector). The common optimal price for all firms in a particular sector is the expected discounted sum of future marginal costs in that sector, as one can see from (27). Equation (28) shows that for every sector the marginal cost is a weighted average of the labour input cost, or the wage, and the intermediate inputs cost. Given that the labour supply schedule is vertical (equation (29)) the nominal GDP equation implies that the wage becomes equal to money supply s_t.

One can now see how introducing intermediate inputs makes the sectoral prices strategic complements. Consider a negative one-time innovation to the monetary policy shock variable r that generates a permanent contraction in the money supply. Under $\delta = 0$, each sector's marginal costs equals the money supply in that period. Hence, the optimal price in every sector is equal and exactly follows the downward path of the money supply. Consequently, for every sector the speed of price adjustment, and hence the short-run effect on sectoral consumption, is determined solely by that sector's own price stickiness, represented by α_k. If one instead allows for a positive share of intermediate inputs ($\delta > 0$), the dynamics of price adjustment to the monetary policy shock becomes more co-ordinated across sectors. In particular, each sector's marginal cost is now a weighted average of the money supply and the prices set in all other sectors, scaled by the input-output weights. As a result, if a sector has a sticky supplier, the supplier's slow price adjustment will transmit into the customer's marginal cost and the optimal price, making the customer's price adjustment slower than it would otherwise be. Such contagion of price stickiness from suppliers to customers creates extra positive co-movement across sectors, which is the very definition of strategic complementarity. In addition, given the slower adjustment of sectoral prices, the degree of short-run money non-neutrality rises and the effect on real variables, such as consumption, becomes larger in the short run. Naturally, other things equal, higher share of intermediate inputs makes sectoral marginal costs more sensitive to suppliers' prices and hence increases the degree of strategic complementarity.

The above is a system of $(4K + 5)$ equations in $(4K + 5)$ unknowns, namely, $(p_{1t}, ..., p_{Kt})$, $(mc_{1t}, ..., mc_{Kt})$,$(p^*_{1t}, ..., p^*_{Kt})$,$(c_{1t}, ..., c_{Kt})$ and $(w_t, p^c_t, c_t, s_t, r_t)$. However, due to a number of asymmetries, such as heterogeneous input weights ω_{kr} and consumption weights ω_{ck} one cannot easily find an analytical solution to the above system. Instead, in the next subsection we will consider a simple calibrated three-sector case ($K = 3$), and will gain further intuition by considering numerically computed impulse responses to a monetary policy shock [3].

[3] Our numerical impulse responses are obtained using Dynare.

2.6 Three-sector economy example ($K = 3$)

In this subsection we focus on a three-sector ($K = 3$) version of our economy and perform two exercises that consider the response of our system to a monetary contraction. In particular, we subject our system to one-time one-standard negative innovation to the monetary policy shock variable r that translates into a permanent contraction of nominal GDP/money supply. Following Shamloo (2010), we calibrate our model to monthly data by setting $\beta = 0.9975, \rho_r = 0.5, \sigma_\varepsilon = 0.0025$, and the consumption shares are set to be equal ($\omega_{c1} = \omega_{c2} = \omega_{c3} = 1/3$).

In our first exercise, Sector 1 is assumed to be almost, but not completely, flexible ($\alpha_1 = 0.1$), Sector 2 is semi-flexible ($\alpha_2 = 0.5$) and Sector 3 is almost completely rigid ($\alpha_3 = 0.9$). The input-output matrix is set to be completely symmetric, so that $\omega_{kr} = 1/3 \quad \forall k, r \in \{1, 2, 3\}$. Figure 1 shows the responses of such system to the permanent contraction in money supply for three different values of the intermediate inputs share $\delta \in (0, 0.4, 0.8)$. We can see that in the economy with no intermediate inputs ($\delta = 0$), the magnitude of the reduction in consumption is proportional to the degree of price stickiness, which is a standard result. As we increase the share of intermediate inputs, the magnitude of reduction in sectoral consumption becomes larger for all sectors, with the ***degree of amplification decreasing in sector's own price stickiness***. This is because more flexible sectors' marginal cost and hence the price set "inherits" stickiness from its rigid suppliers, unlike the more rigid sectors whose price setting is already very staggered. Also, other things equal, we can see that the ***degree of amplification increases in the economy's share of intermediate inputs*** δ. This is because higher δ means that the sensitivity of marginal cost to suppliers' prices is higher and hence allowing for stringer "inheritance" of stickiness.

In our second exercise, Sector 1 is completely flexible ($\alpha_1 = 0$) with the other sectors remaining unchanged from the previous exercise ($\alpha_2 = 0.5, \alpha_3 = 0.9$). In addition, firms in Sector 1 are assumed to be buying inputs only from other firms in Sector 1 ($\omega_{11} = 1, \omega_{12} = \omega_{13} = 0$), whereas the input-output weights for the other two sectors are as in the previous exercise ($\omega_{kr} = 1/3 \quad \forall k, r \in \{2, 3\}$). Figure 2 shows the responses to the monetary contraction. As before, for $\delta = 0$, the magnitude of sectoral consumption fall is proportional to the degree of price stickiness, with the fully flexible Sector 1 exhibiting no change in sectoral consumption, as its price index adjusts one-for-one with the money supply. Most importantly, as we increase δ, Sector 2 and Sector 3 experience greater decrease in consumption, whereas Sector 1 still showing no response. The latter highlights the fact that the amplification of consumption response is due to ***downstream propagation*** of price stickiness, as it travels from suppliers firms to customer firms. Indeed, firms in Sector 1 do not purchase inputs from the sticky Sectors 2 and 3 and only from other fully flexible firms in their own sector. Hence, firms in Sector 1 do not inherit any stickiness from the other sectors and experience no amplification.

2.7 From theory to empirics: analytical solution with myopic firms

In this section we follow Pasten et al. (2016) and consider a version of our model, where firms fully discount the future when choosing their optimal price. The latter is equivalent to setting $F_{t,t+s} = 0 \quad \forall s > 0$ in equation (11). The latter yields the following expression for the optimal price in sector k:

$$P^*_{kt} = \frac{\theta}{\theta - 1} MC_{kt}, \tag{34}$$

or $p^*_{kt} = mc_{kt}$ when log-linearised. As the rest of the model remains unchanged, we can summarise the log-linearised equilibrium as:

$$p_{kt} = \alpha_k p_{k,t-1} + (1 - \alpha_k)(1 - \delta)s_t + (1 - \alpha_k)\delta \sum_{r=1}^{K} \omega_{kr} p_{rt}, \quad k = 1, 2, ..., K \tag{35}$$

$$c_{kt} = s_t - p_{kt}, \quad k = 1, 2, ..., K \tag{36}$$

$$c_t = \sum_{k=1}^{K} \omega_{ck} c_{kt} \tag{37}$$

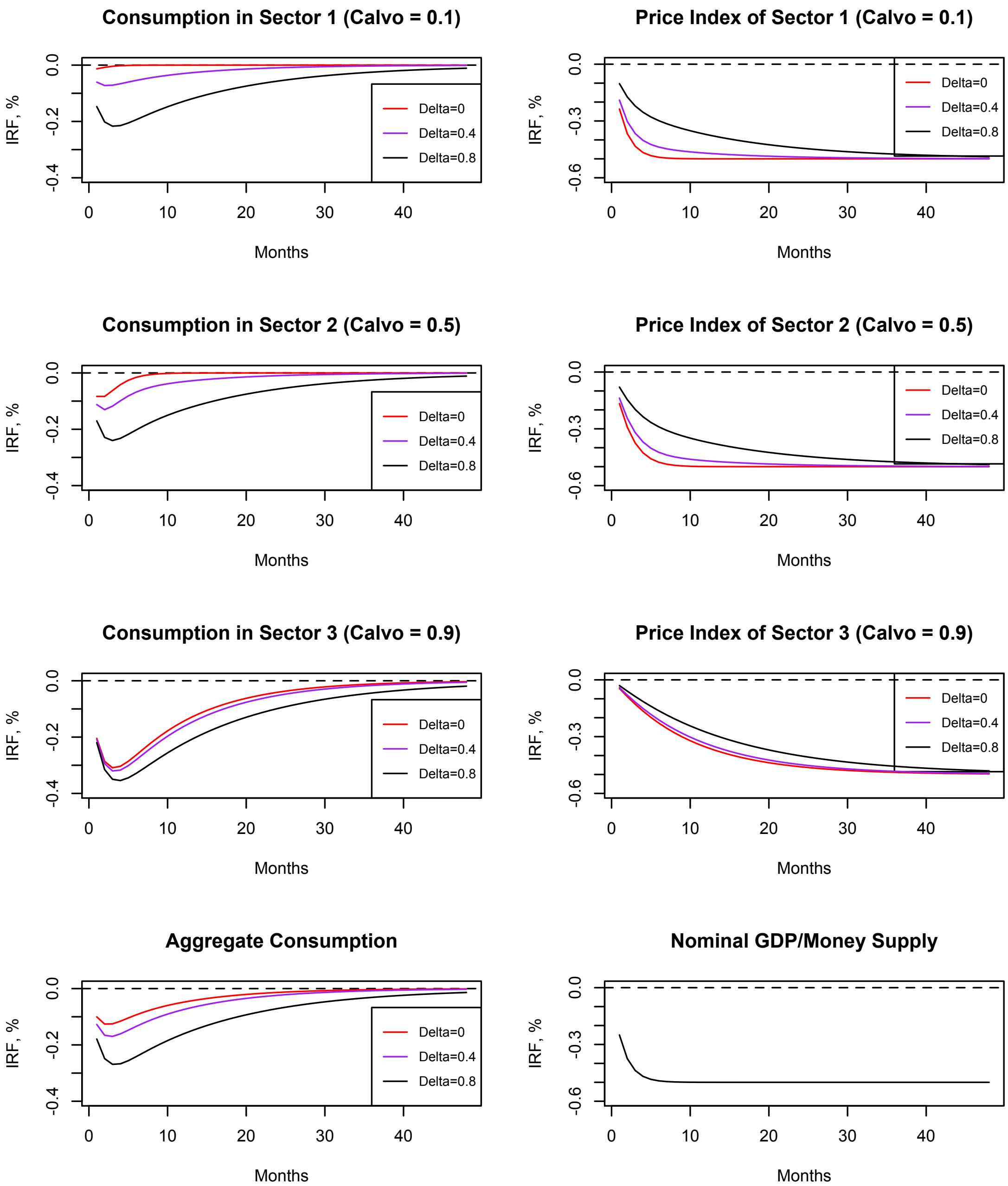
$$s_t = s_{t-1} + r_t, \quad r_t = \rho_r r_{t-1}, + \epsilon_t, \quad \{\varepsilon_t\}_t \sim i.i.d.(0, \sigma^2_\varepsilon). \tag{38}$$

Given that the aim of our empirical exercise is to examine the effect on consumption, we can combine (35) and (36) to find an expression for sectoral consumption:

$$c_{kt} = \alpha_k c_{k,t-1} + \alpha_k s_t - \alpha_k s_{t-1} + (1 - \alpha_k)\delta \sum_{r=1}^{K} \omega_{kr} c_{rt}. \quad k = 1, 2, ..., K \tag{39}$$

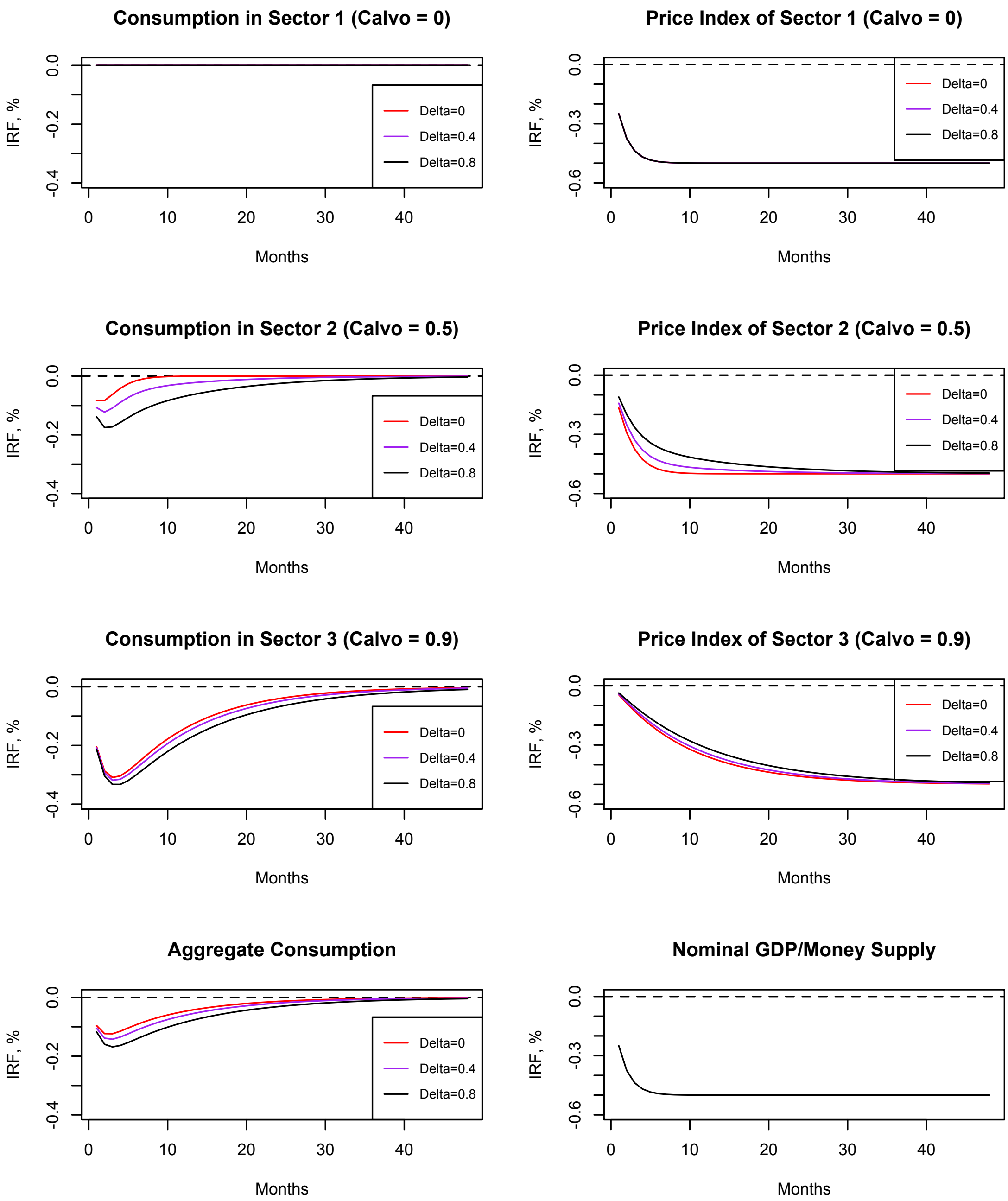
Analysing the expression in (39), we can see that following a monetary policy shock, there are two channels through which sectoral consumption is getting affected.

Figure 1: Responses of sectoral consumptions and price indices to a monetary contraction



Note: The figure is constructed by calibrating (26)-(33) for $K = 3$ *and considering a one-time one standard deviation negative innovation to the monetary policy shock variable that generates a permanent contraction in money supply. The impulse responses are found numerically using Dynare.*

Figure 2: Responses of sectoral consumptions and price indices to a monetary contraction



Note: The figure is constructed by calibrating (26)-(33) for $K = 3$ and considering a one-time one standard deviation negative innovation to the monetary policy shock variable that generates a permanent contraction in money supply. The impulse responses are found numerically using Dynare.

Firstly, there is the own persistence channel, or the ***direct effect***, given by the term $\alpha_k c_{k,t-1} + \alpha_k s_t - \alpha_k s_{t-1}$ and is driven by the own price stickiness, and hence own non-neutrality, of the firms in a particular sector. Indeed, we can see that this effect increases in the degree of own stickiness in a particular sector, captured by α_k as the proportion of firm that fail to adjust to optimal price in any period.

Secondly, there is the production networks persistence channel, or the ***downstream effect***, given by the term $(1-\alpha_k)\delta \sum_{r=1}^{K} \omega_{kr} c_{rt}$. Indeed, if there are sectors that exhibit a lot of non-neutrality, a sector can "inherit" this non-neutrality to the extent to which it buys inputs from those sectors (as captured by the weight ω_{kr}) and hence to the extent to which its marginal cost, and thus the price, inherits the stickiness. The reason we call it a downstream effect is because the contagion of stickiness goes from supplier firms to customer firms and not the other way round.

We can also see that, other things equal, the downstream effect decreases in the own stickiness α_k, as it is easier for a relatively flexible sector to inherit the extra stickiness from its suppliers than its for a sector that is already very sticky on its own. Also, other things equal, the downstream effect increases in the share of intermediate inputs δ. As we can see from (28), this is because higher δ makes the marginal cost more sensitive to suppliers' price and hence allows for stronger contagion of stickiness. The above results are exactly what we saw in our three-industry example.

3 Data

This section contains an overview of the data used in our empirical analysis. We build our dataset for the United States. More details on the dataset as well summary statistics are given in the Appendix.

3.1 Sectoral consumption

We use the underlying detail tables of NIPA accounts published by the Bureau of Economic Analysis (BEA) to obtain monthly sectoral nominal Personal Consumption Expenditure (PCE) and PCE Price Index data from 1976:1 until 2015:12, where the start date was chosen to maximise the number of industries available. In order to construct real PCE series, we combine nominal PCE and PCE Price Index data.

However, the classification used in the NIPA tables does not match that from the BEA Input-Output (IO) accounts that will be used to construct our input-output weights. In order to match NIPA series to BEA IO accounts we use PCE Bridge Tables also published by the BEA. The latter Bridge Tables are available at two levels of aggregation: Summary and Detail that roughly correspond to 3-digit and 6-digit NAICS codes precision levels respectively. We construct BEA IO Accounts consistent sectoral consumption series at both levels of aggregation. The full list of sectors at each level of aggregation is available in the Appendix.

At the Detail level, we have constructed data for 231 sectors going from 1987:1 until 2015:12 where some sectors had to be deleted due to lack of data and the starting point had to be shifted forwards to 1987:1 to minimise the number of industries to be deleted. Apart from the advantage of a much more detailed sectoral data, the disadvantage of the Detail level accounts is that the PCE Bridge Table is only available for the year 2007, which is the table we use to match series for the entire duration of the sample under the assumption that the matching is remaining stable throughout. Overall, over the sample, the sectoral consumption series constructed account for around 82 per cent of aggregate real Personal Consumption Expenditure (PCE).

At the less disaggregated Summary level, we have only constructed data for 58 sectors, but the advantages of the this level of granularity are the longer time series available (1976:1 until 2015:12) and that the PCE Bridge Tables are available annually from 1997 until 2015, so the assumption about the matching stability can be somewhat examined. The consumption series constructed account for around 91 per cent of aggregate real Personal Consumption Expenditure (PCE) over the sample.

We conduct (Augmented) Dickey-Fuller tests to assess the stationarity of our consumption series. Non-stationarity cannot be rejected for most sectoral consumption series at both levels of aggregation, forcing us to perform a stationarity inducing transformation, that is expressing all consumption series in growth rates. Reassuringly, all growth rates series are found to be stationary.

3.2 Input-output weights

Recall that in the Model section we established that in equilibrium the input-output weight ω_{kr} is the proportion of the total expenditure of a firm in sector k on intermediate inputs that goes to intermediate inputs produced in sector r. Following aggregation over all firms in a given sector, we can write ω_{kr} as:

$$\omega_{kr} = \frac{P_{rt} Z_{kt}(r)}{P_t^k Z_{kt}}, \qquad \forall k, r \tag{40}$$

so that it is now the proportion of total expenditure of sector k on intermediate inputs that goes to intermediate inputs produced in sector r.

As part of its Input-Output accounts, the US Bureau of Economic Analysis publishes annual "$Make$" and "Use" tables that can be used to evaluate the numerator and the denominator in (40) for any sector pair. The "$Make$" tables show how much of a given product is produced by a particular sector, measured in nominal (US dollar) terms. The "Use" tables show how much a given product is used as an intermediate input by a given sector (as well as its use by final users), again measured in nominal (US dollar) terms. Assume that our products are indexed by $q \in \{1, 2, ..., Q\}$.To calculate the $P_{rt} Z_{kt}(r)$ component, or the nominal value of inputs sold by sector r to sector k, we first work out the market share of sector r in the production of product q, given by $Share_{r,q}$, using the $Make$ table:

$$Share_{r,q} = \frac{Make_{r,q}}{\sum_{r'=1}^{K} Make_{r',q}}, \tag{41}$$

where $Make_{r,q}$ denotes the nominal value of sector r's production of product q. Later, we take the nominal expenditure of sector k on every product q as an intermediate input, given by $Use_{k,q}$, and find out how much of this expenditure goes to sector r by multiplying it by r's respective market share. The latter gives us the empirical counterpart of $P_{rt} Z_{kt}(r)$, or total nominal sales of intermediate inputs from sector r to sector k:

$$Sales_{r,k} = \sum_{q=1}^{Q} Share_{r,q} Use_{k,q}. \tag{42}$$

Finally, the empirical counterpart of $P_t^k Z_{kt}$, or the total expenditure of sector k on intermediate inputs, is given by $\sum_{r'=1}^{K} Sales_{r,k}$ and hence ω_{kr} can be evaluated as:

$$\omega_{kr} = \frac{Sales_{r,k}}{\sum_{r'=1}^{K} Sales_{r',k}}, \qquad \forall k, r. \tag{43}$$

Note that the number of sectors considered in "$Make$" and "Use" tables is generally larger than that available in PCE Bridge Tables and can be matched to sectoral consumption in NIPA Tables. This is because PCE Bridge Tables exclude sectors that either don't sell anything to final consumers or those whose final consumption only accounts for a very small proportion of total output. For example, at Detail level, "$Make$" and "Use" tables consider 389 industries, whereas PCE Bridge Tables only include data on 257 of them. After organising our input-output weights into an input-output matrix Ω, so that $\omega_{kr} = [\Omega]_{k,r}$, we delete rows and columns for sectors that are not represented in PCE Bridge Tables and therefore don't sell a large enough proportion of their output to final consumers. In order to satisfy our theoretical requirement that the input-output weights add up to one for any sector, we normalise the rows of the reduced input-output matrix.

In addition we also use the "Use" tables to construct the consumption weights $\{\omega_{ck}\}_{k=1}^{K}$ considered in the model section. Recall that in equilibrium those are given by:

$$\omega_{ck} = \frac{P_{kt}C_{kt}}{P_t^c C_t}, \tag{44}$$

or the proportion of total nominal consumption expenditure that goes to goods produced in sector k. The "Use" tables contain information on Private Consumption Expenditure (PCE) for every sector that year (the empirical equivalent of $P_{kt}C_{kt}$) as well as aggregate nominal Private Consumption Expenditure (PCE) that year (the empirical equivalent of $P_t^c C_t$). We use the above empirical equivalents to construct the empirical consumption weights.

At Detail level, "$Make$" and "Use" tables are only available for the year 2007, and so we construct both input-output and consumption weights based on the 2007 tables. At Summary level, those tables are available every year between 1997 and 2015; we have estimated input-output and consumption weights for every year those tables are available. However, upon inspection, the constructed weights show very little variation over time. As a result, for Summary level we have decided to use weights for the year 2007 for the ease of comparison with the Detail level.

3.3 Monetary policy shocks

Our baseline measure of US monetary policy shocks comes from Romer and Romer (2004), who use the Greenbook forecasts to decompose changes in the federal funds rate into expected and unexpected (shock) components. The original Romer and Romer (2004) dataset contains monthly shocks from 1969:1 until 1996:12. Wieland and Yang (2015) extend Romer and Romer (2004) shocks until 2007:12, right before the US enters the Zero Lower Bound period.

We also consider monetary policy shocks identified using different strategies. Firstly, we consider shocks identified from a structural vector autoregression (SVAR) that features industrial production, unemployment, consumer price index (CPI), commodity price index and the effective federal funds rate.[4] The recursive Cholesky identification strategy is used with the effective federal funds rate ordered last. Following Coibion (2012) we exclude the period of non-borrowed reserved targeting by the US Federal Reserve and estimate our SVAR using monthly data between 1984:1 and 2007:12 with 12 lags.

Secondly, we consider monetary policy shocks identified using event studies and high frequency data, as in Kuttner (2001) and Gürkaynak, Sack and Swanson (2005). In particular, we use data from Gentler and Karadi (2015) on monthly shocks identified as changes in current month's federal funds futures within 30-minute windows around monetary policy announcements. It could be argued that those changes reflect unexpected changes in monetary policy decisions and can thus be interpreted as monetary policy shocks. One disadvantage of this approach is that these shocks rely on data on federal funds futures that have only been traded on the Chicago Board of Trade Exchange since 1988:10 (Gürkaynak, Sack and Swanson, 2005). Hence these shocks are only available from 1988:11 (and until 2007:12 for our purposes).

In the Appendix, we provide some summary statistics and time series plots for all three monetary policy shocks measures.

[4] In order to estimate the SVAR, with use the dataset provided with Coibion (2012).

3.4 Estimation sample

Our baseline estimation sample is using Detail level sectoral consumption (231 sectors) and the extended Romer and Romer (2004) monetary policy shocks. The timing of our baseline sample is between 1987:1 and 2007:12.

In the Robustness checks section, among other things, we discuss the results obtained using Summary level sectoral consumption (58 sectors) and different measures of monetary policy shocks (described in the previous subsection). Although Summary level sectoral consumption is available from 1976:1, we still begin our sample in 1987:1 for greater comparability with the Detail level results. When SVAR monetary policy shocks are used, the sample remains unchanged (1987:1-2007:12). With shocks identified using event studies, we begin our sample in 1988:11, as dictated by the availability of federal funds futures data.

4 Econometric strategy

4.1 Baseline specification

Our baseline specification is motivated by the equilibrium condition (39) for sectoral consumption derived in the Model section:

$$\Delta c_{kt} = \eta_{k0} + \sum_{j=1}^{12} \eta_{kj} \Delta c_{k,t-j} + \sum_{j=1}^{24} \phi_{kj} r_{t-j} + \sum_{j=1}^{12} \psi_{kj} \sum_{r=1}^{K} \omega_{kr} \Delta c_{r,t-j} + \epsilon_{kt}, \tag{45}$$

$k = 1, 2, ..., K; t = 1, 2, ..., T$; where c_{kt} is log sectoral consumption in sector k at time t, r_t is monetary policy shock at time t, $\{\omega_{kr}\}_{k,r}$ are the input-output weights that we constructed in the Data section, $\{\epsilon_{kt}\}_t \sim i.i.d.(0, \sigma_k^2)$ is a sector-specific idiosyncratic shock process. We have included one year of own lags, one year of lagged downstream effects and two years of lagged monetary policy shocks for empirical soundness. However, we test the sensitivity of our results to different lag structures in the Robustness checks section.

Note that we have made some changes compared to the theoretical expression for sectoral consumption given in (39). Firstly, our baseline regression is specified in growth rates, as opposed to log-levels, which reflects the evidence of non-stationarity in sectoral consumption that we outlined in the Data section and hence the need for a stationarity-inducing transformation. Secondly, in the theoretical expression the downstream effects are contemporaneous, whereas in our regression specification they are lagged by at least one period. This is our identifying restriction, as otherwise we would encounter the problem of simultaneity and the coefficients on downstream effects $(\psi_{k1}, ..., \psi_{k12})$ would not be identified without further restrictions. Given that we are using monthly data, the assumption of no downstream effects within the same month is likely to be valid. For example, this could be because inputs are supplied according to pre-written long-term contracts that prespecify the prices of inputs. As a result, inputs prices may be affecting marginal cost with a delay. Thirdly, to avoid any timing mis-matches between direct and downstream effects we assume that monetary policy shocks have no effect on consumption within the same month[5], which, although not necessary in our case, is a standard assumption in the monetary policy literature.[6]

4.2 Coefficient estimation

The specification in (45) is a dynamic panel that allows for different estimation approaches depending on the degree of coefficient homogeneity one is willing to assume.

On the one hand, one could assume that $\eta_{kj} = \eta_j, \phi_{kj} = \phi_j, \psi_{kj} = \psi_j \quad \forall k, j$ and treat η_{k0} as a sector-specific fixed effect. This is the approach followed by, among others, Acemoglu, Akcigit and Kerr (2015). Under such assumptions, Fixed Effects (FE) estimation would deliver consistent estimators of $\{\eta_j, \phi_j, \psi_j, \eta_{k0}\}_{j,k}$ with good small sample properties, as the time dimension is sufficiently large (21 years of monthly data)[7] for the Nickell (1981) dynamic panel bias to be small. However, such strong homogeneity assumption is mostly certainly going to be false. Indeed, even in our parsimonious theoretical expression for sectoral consumption, our coefficients are function of sector-specific probabilities of price adjustment that

[5]Our results are robust to the inclusion of contemporaneous effects of monetary policy shocks

[6]Such timing assumption is often made in both single-equation approach studies (Romer and Romer, 2004) as well as studies using structural vector autoregressions (SVAR) (Christiano, Eichenbaum and Evans, 1999)

[7]Simulations in Judson and Owen (1999) show that for dynamic panels with T larger than 30, FE is indeed the preferred estimator

empirically exhibit a lot of heterogeneity. Indeed, Nakamura and Steinsson (2008), estimate frequencies of price adjustment in producer prices and report significant heterogeneity across sectors. In addition, Boivin, Giannoni and Mihov (2009) report significant heterogeneity in impulse responses of producer prices to both aggregate and idiosyncratic shocks. As shown by Pesaran and Smith (1995), under coefficient heterogeneity in dynamic panels, Fixed Effects (FE) does not deliver consistent estimates of coefficient means and the estimates cannot be given a straightforward interpretation.

One could instead allow for full heterogeneity in coefficients and estimate (45) using the Mean Group estimator (Pesaran and Smith, 1995) in order to obtain consistent estimates of the coefficient means. The latter would entail estimating (45) separately for every sector and then finding coefficient means across sectors. However, the Mean Group estimator requires an additional assumption of no cross sectional dependence of the error terms. Given the parsimonious nature of our specification in (45), the idiosyncratic errors are most certainly going to be correlated over the sectors. One reason is that there are other common factors, apart from monetary policy shocks, that influence sectoral consumption, such as aggregate fiscal shocks or aggregate productivity shocks. The error term ϵ_{kt} most likely has the form $\epsilon_{kt} = g_t + \nu_{kt}$, where g_t sums up all other aggregate influences and $Cov(\nu_{kt}, \nu_{rt}) = Cov(\nu_{kt}, g_t) = 0 \quad \forall k, r, t$. We can thus see that under such error structure $Cov(\epsilon_{kt}, \epsilon_{rt}) = Var_(g_t) \neq 0 \quad \forall k, r, t$. One approach to deal with the above issue would be to proxy for the unobserved common factors with principal components of a large number of aggregate macroeconomic series. However, one would then need to additionally model responses of those principal components to a monetary policy shock (including the contribution of the downstream effect), which is beyond the scope of this paper.

We are therefore left with no choice, but to estimate (45) separately for every sector by OLS without performing any aggregation afterwards. The latter should not be an issue, as under our baseline sample and specification we have 21 years of monthly data for every sector and 50 parameters to be estimated per sector.

4.3 Impulse responses

After estimating the coefficients for every sector, we compute two impulse responses for every sectoral consumption. The first one is a full impulse response to an unexpected 25 basis points monetary policy tightening where we allow for both direct and downstream effects. The second one is a restricted impulse response, where we impose that $\hat{\psi}_{kj} = 0 \quad \forall k, j$ and thus block the downstream effects. The difference between the two impulse responses should reflect the downstream effect for that particular sector.

To get a sense for the overall strength of the downstream effect versus the direct effect we consider both full and restricted impulse responses aggregated over the sectors. We aggregate the impulse responses by finding a weighted mean response at every horizon, where the weights are either given by the respective sectoral consumption weights $\{\omega_{ck}\}_{k=1}^{K}$, or equal weights $1/K$ are used for all sectors. The difference between the aggregated full impulse responses and the aggregated restricted impulse response should reflect the overall importance of the downstream effect in the US economy.

For reference, we compare our aggregated full impulse response to the impulse response of aggregate real Personal Consumption Expenditure (PCE)[8] for which we perform the Romer and Romer (2004) exercise:

$$\Delta c_t = \tilde{\eta}_0 + \sum_{j=1}^{12} \tilde{\eta}_j \Delta c_{t-j} + \sum_{j=1}^{24} \tilde{\phi}_j r_{t-j} + \tilde{\epsilon}_t, \qquad t = 1, 2, ..., T. \tag{46}$$

5 Baseline results

5.1 Sectoral consumption responses

Figure 3 shows impulse responses for all 231 sectors in our baseline sample to an unexpected 25 basis points tightening; in addition, it also reports weighted and unweighted aggregations as well as the response of aggregate real PCE.

Several aspects are worth highlighting. Firstly, there is significant heterogeneity in the responses, which further validates our strategy sector-by-sector estima-

[8] We obtain data on US real Personal Consumption Expenditure (PCE) from the Bureau of Economics Analysis (BEA) NIPA accounts.

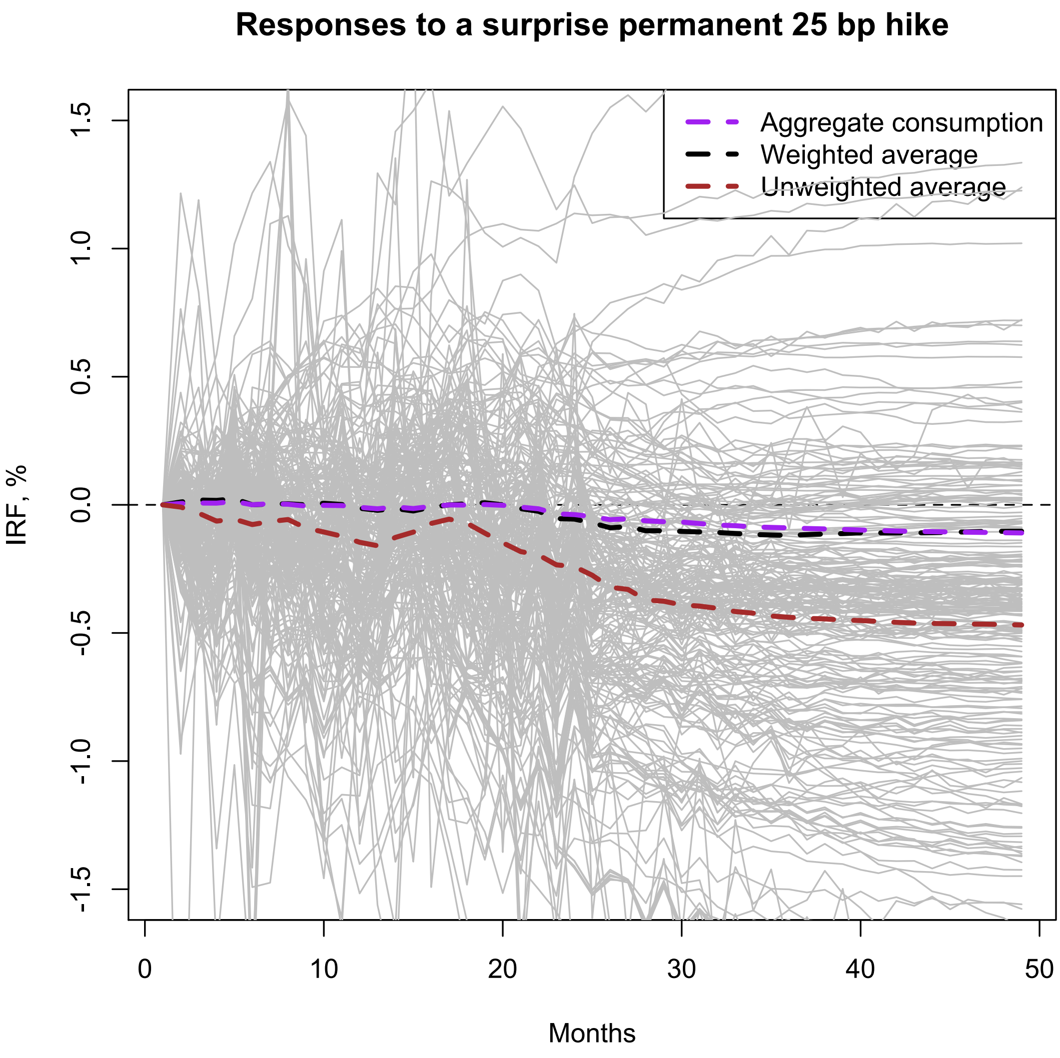
tion. Secondly, the aggregate response obtained by weighing individual responses by their respective consumption weights follows the aggregate real PCE response very closely, and much more closely than the unweighted aggregation. This suggests that the aggregate response may be driven by several large sectors. The weighted aggregated response predicts a peak drop in consumption of around 0.12 per cent, which is close to the result in Boivin, Giannoni and Mihov (2009) who aggregate estimated product-level consumption responses. Particularly reassuring is the fact that Boivin et al. (2009) obtain their results from a Factor-Augmented Vector Autoregression (FAVAR), which is a very different identification strategy from the one used in our paper.

However, certain aspects of our results also somewhat puzzling. Firstly, one slightly worrying aspect is the fact that the impulse responses generally do not converge back to zero, which strictly speaking violates long-run money neutrality. As discussed in Cloyne and Hürtgen (2016), this long-run error in impulse responses is a general feature of the single equation approach to estimation of the effect of monetary policy shocks. Their suggestion to circumvent this issue is to use local projections, as introduced by Jorda (2005). We leave the application of local projection to our problem for further research. Given this long-run error, for the rest of the paper we will only focus on the peak effect, and will not attach much meaning to the long-run response.

Secondly, and related to the previous point, as we can see in Figure 4, there is heterogeneity across sectors in the horizon at which peak consumption drop is achieved and those don't generally match the horizon at which we observe peak in the aggregate response. It could therefore be that we are partly aggregating long-run errors rather than genuine sectoral consumption responses. We address this issue in the Robustness checks section, where we provide some evidence that our results are in fact not driven by the long-run errors.

Thirdly, quite a number of sectors appear to be experiencing an increase in their consumption following a monetary tightening, as we can see even more clearly in Figure 5. The latter phenomenon was also documented by Boivin et al. (2009) in their FAVAR study of product-level consumption responses. Not only this appears slightly puzzling at first, such "inverted" consumption responses cannot be

Figure 3: Responses of sectoral consumptions to 25bp tightening (Detail level, 231 sectors) – Romer-Romer shocks



Note: The figure reports full impulse responses of all 231 sectors available under Detail level to an unexpected one-time 25bp tightening. The Weighted average is constructed by finding the weighted average response at every horizon with the consumption shares $\{\omega_{ck}\}_{k=1}^{231}$ *used as weights. The Unweighted average is constructed by finding the unweighted average response at every horizon. The Aggregate consumption line is the impulse response of the aggregate real PCE.*

generated by the model we introduced earlier. However, in Section 7 we show how a very slight and plausible modification to our model can in fact generate positive consumption responses to a monetary tightening.

Fourthly, the downstream effect does not increase the magnitude of peak consumption response for all sectors. For every sector, the contribution of downstream effect is evaluated as the difference between peak consumption response in full and restricted impulse responses, expressed as a percentage of the former. Figure 6 shows that for the vast majority of sectors, the contribution of downstream effect is positive and lies between 0 and 100 per cent, as predicted by our theory. However, most notably, there are some sectors for which the contribution is in fact negative. Negative contribution can occur in one of two cases: either the peak consumption was positive under direct effect and adding downstream effect made it less positive; or it was negative under direct effect and was made less negative by adding the downstream effect. In Section 7 we present a modified version of our model that can reconcile the above cases.

5.2 Decomposing the aggregated consumption response

Figure 7 shows the decomposition of the weighted aggregated consumption response into the direct and the downstream effect.[9] The black line corresponds to the dashed black line in Figure 3 and represents the total (direct and as well downstream) effect. The red line is the weighted aggregation of the restricted impulse responses and thus represents the direct effect only. The green line is the difference between the black and the red line and visualises the downstream effect. [10]

Firstly, one can see that at the peak, the full effect of a 25bp tightening is a

[9]For presentational purposes, the aggregated impulse responses presented in decomposition plots in the main body of this paper have been smoothed with a 4-period moving average transformation. In the Appendix, we present the original non-smoothed aggregated impulse responses. One can observe that none of our quantitative results are sensitive to performing the smoothing.

[10]Ideally, one would also want to include confidence bands around the aggregated impulse responses in order to assess the statistical significance of the estimated effects. However, given the complex interdependencies across the sectoral impulse responses introduced by production networks, we have not been able to come up with a feasible procedure to construct confidence bands. We leave this very important task for future work.

Figure 4: Peak horizons (Detail level, 231 sectors)

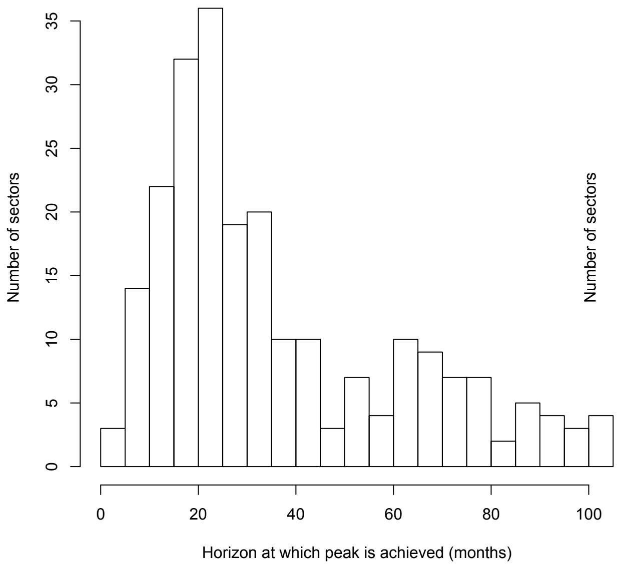


Figure 5: Peak consumption responses (Detail level, 231 sectors)

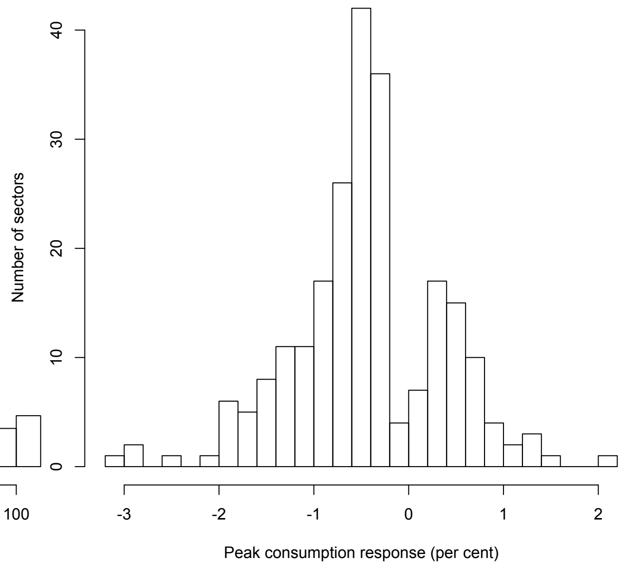
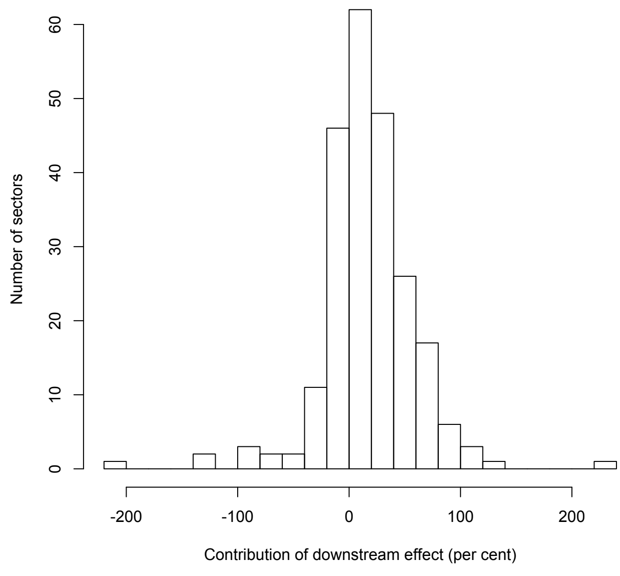


Figure 6: Contribution of downstream effect to peak consumption response (Detail level, 231 sectors)



Note: Figure 4 shows the histogram for the horizons at which sectors experience their peak consumption response; Figure 5 is the histogram of peak consumption responses across sectors; Figure 6 shows the histogram of contributions of the downstream effect to each sector's full response, which is evaluated as the difference between peak full response and peak restricted response expressed as a percentage of the former.

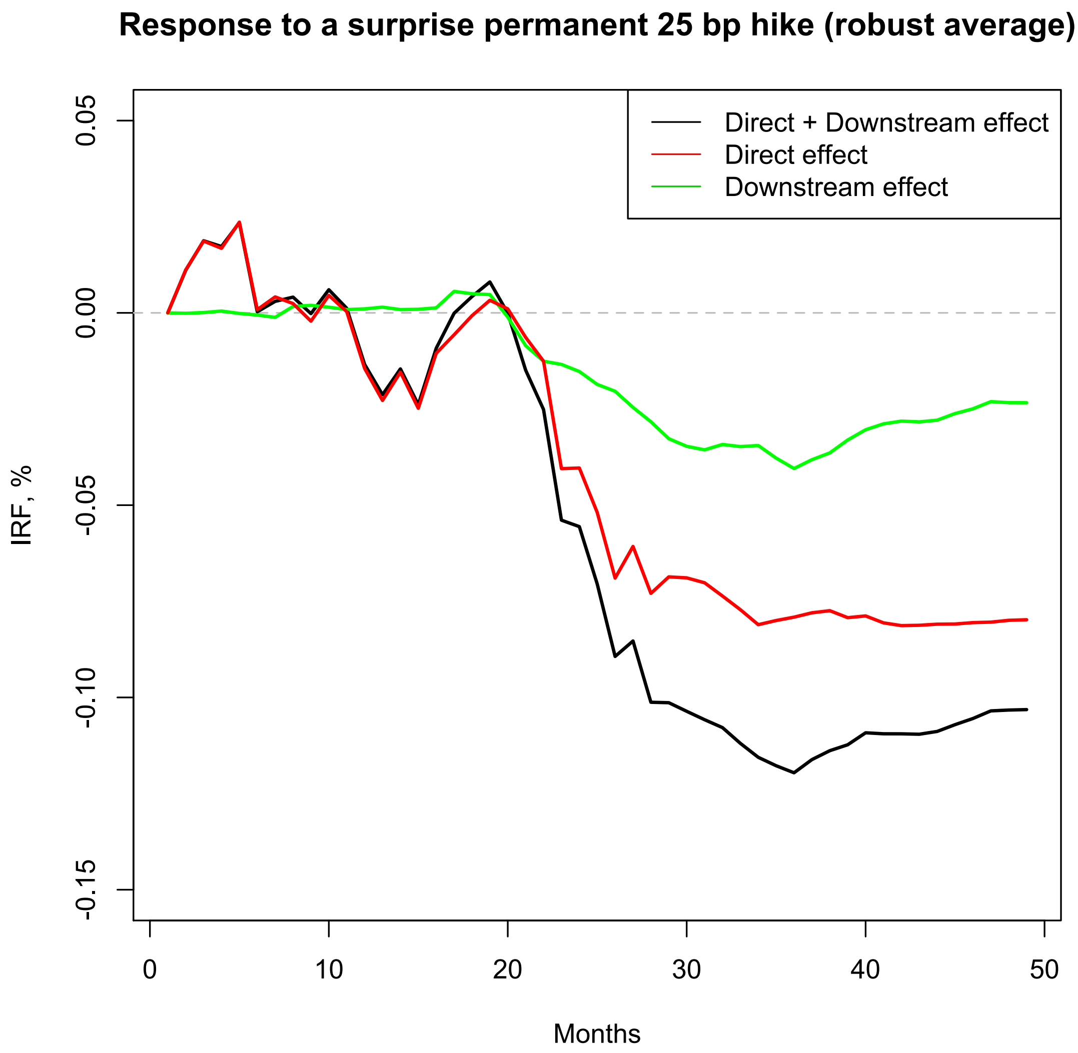
drop of around 0.12 per cent in consumption, whereas the direct effect will only generate a drop of around 0.08 per cent. Hence, at the peak, ***the downstream effect accounts for around 33 per cent of the effect of monetary policy shocks on US consumption***.

Secondly, it can be observed that ***the downstream effect comes in after a noticeable lag of around 18 months***. This is an intuitively plausible feature that also gives extra validity to our identifying assumption of no downstream effect within the same month. As we argued earlier, one reason for these observed lags is the fact that inputs are supplied according to pre-written long-term contracts, so that sectoral prices affect nominal marginal cost with a delay. Of special interest is the fact that neither our simple calibrated examples in Section 2 nor larger calibrated models (such as Pasten et al., 2016) exhibit such lags. Developing DSGE models that generate such delays postulates an interesting research agenda.

Although this is the first paper to econometrically estimate the contribution of production networks to the response of consumption, or in fact any other macroeconomic aggregate, to a monetary policy shock, some comparison with the related literature would still be useful. Ozdagli and Weber (2016) study the response of stock prices to monetary policy shocks and attribute 50 to 85 per cent to production network effects, which is somewhat higher than our estimate. Acemoglu, Akcigit and Kerr (2015) focus on the effect of real idiosyncratic shocks (sectoral government spending, factor productivity, patenting and imports) on sectoral output, employment and labour productivity. They find that production networks account for up to 90 per cent of the total effect, this time substantially higher than our estimate. Overall, our estimated degree of amplification appears smaller than estimated in other contexts.

Another important point is that Acemogu, Akcigit and Kerr (2015) find that supply-side shocks propagate downstream, whereas demand-side shocks propagate upstream. Our result that monetary policy shocks (that are demand-side) propagate downstream is not contradictory, for two main reasons. Firstly, from theoretical perspective, their results rely on a flexible price framework of Long and Plosser (1983) where demand-side shocks do not affect prices and hence have no effect on consumption at all. On the contrary, the effect of monetary policy shocks on

Figure 7: Impulse response decomposition (Detail level, 231 sectors) – Romer-Romer shocks



Note: The Direct+Downstream effect line corresponds to the Weighted average line in Figure 3 and is the weighted average response at every horizon. The Direct effect is found by computing weighted average restricted impulse response at every horizon. The Downstream effect represents the difference between the two other lines and quantifies the contribution of the downstream effect. For presentational purposes, 4-period moving averages of the aggregated responses are shown in the figure. The original, non-smoothed impulse responses are reported in the Appendix.

prices and consumption is a crucial ingredient of our framework. Secondly, from the empirical perspective, Acemoglu, Akcigit and Kerr's (2015) findings are for sectoral output, employment and labour productivity, and not for sectoral consumption.

6 Robustness checks

6.1 Level of aggregation

We are now going to consider the extent to which our results are robust to using the less disaggregated Summary accounts with only 58 sectors. Recall that despite the smaller level of detail, Summary accounts cover a larger share of aggregate consumption.

Figure 8 shows the sectoral consumption responses for all 58 sectors to a 25 basis points tightening. As with the Detail level accounts, there is a lot of heterogeneity in responses, with positive and negative responses present. Weighted aggregation is still closer to the aggregate PCE response, but the difference between weighted and unweighted aggregations is smaller than in the baseline case. The latter suggests that at Summary level our results are to a lesser extent driven by particular sectors. The magnitude of the peak drop of consumption is marginally higher than using the Detail accounts.

In terms of decomposition, shown in Figure 9, at the peak, full effect delivers a drop in consumption of around 0.17 per cent, whereas direct effect would only deliver a drop of around 0.12 per cent. Hence the downstream effect account for around 30 per cent of the peak effect of monetary policy shocks on consumption. The downstream effects still comes in with a lag, although the delay is somewhat less pronounced compared to baseline results. This could be because with the less disaggregated Summary level it is econometrically more difficult to distinguish between own persistence and the persistence inherited from other firms within the same sector.

Overall, we can see that our baseline results are generally robust to varying the degree of sectoral aggregation.

Figure 8: Responses of sectoral consumptions to 25bp tightening (Summary level, 58 sectors) – Romer-Romer shocks

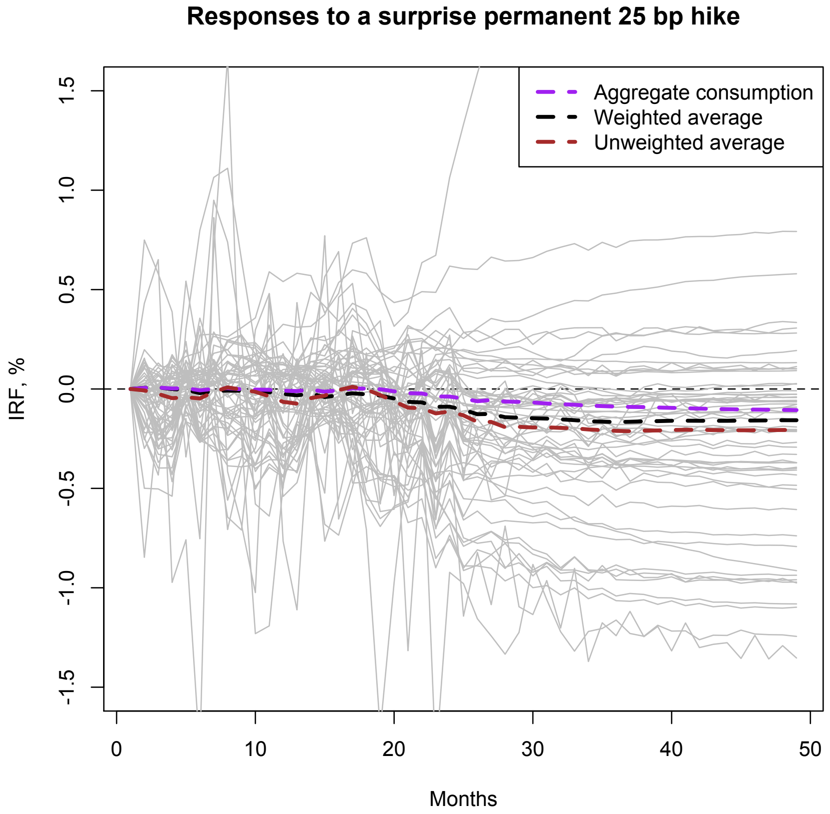
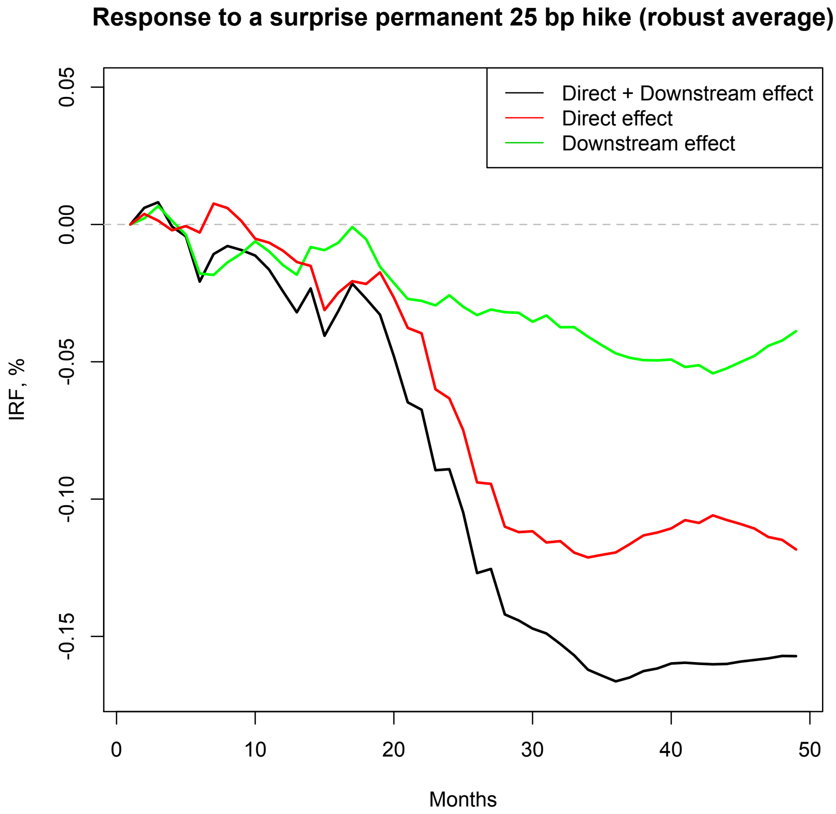


Figure 9: Impulse response decomposition(Summary level, 58 sectors) – Romer-Romer shocks



6.2 Alternative monetary policy shocks

In this subsection we are going to consider results based on two different monetary policy shocks series, described in Section 3.

Figures 10 and 11 show the results obtained using monetary policy shocks identified from the structural vector autoregression (SVAR) that we described in the Data section. As before, following a surprise 25 basis points tightening, there is a lot of heterogeneity in sectoral consumption responses, with both positive and negative responses present. As in the baseline case, the weighted average aggregation is considerably closer to the aggregate real PCE response than the unweighted one, highlighting the presence of some disproportionally large sectors. However, in terms of the magnitude of the response, SVAR identified shocks generate a larger aggregate drop in consumption. At the peak, weighted aggregation predicts a drop of around 0.51 per cent, as opposed to around 0.12 per cent when using Romer and Romer (2004) shocks. We leave it to further research to explain the difference, but what is somewhat reassuring is that the weighted aggregation and aggregate real PCE response are still reasonably close.

Whereas the full effect corresponds to a fall of around 0.51 per cent in consumption at the peak, the direct effect only generates a peak group of roughly 0.39 per cent. Hence, under SVAR identified shocks, downstream effect accounts for around 24 per cent of the overall peak drop in consumption which is less than 33 per cent under Romer and Romer (2004) shocks. The delay in the downstream effect remains noticeable, just like in the baseline case.

As discussed in Section 3, shocks identified using event studies and federal funds futures data are available over a shorter time period. Given the lag structure of our baseline specification, our sample is from 1990:11 until 2007:12. From Figure 12 we can see that using shocks identified from event studies, there is still a lot of heterogeneity, with even more dispersion of sectoral consumption responses compared to baseline results. Weighted aggregation is still closer to aggregate real PCE response compared to the unweighted case. However, the fit of the weighted aggression to the real PCE response is somewhat worse than in the baseline approach. In terms of magnitudes, the weighted aggregation approach predicts a drop in consumption of around 0.5 per cent at the peak, which is closer to the results under SVAR identified

Figure 10: Responses of sectoral consumptions to 25bp tightening (Detail level, 231 sectors) – SVAR shocks

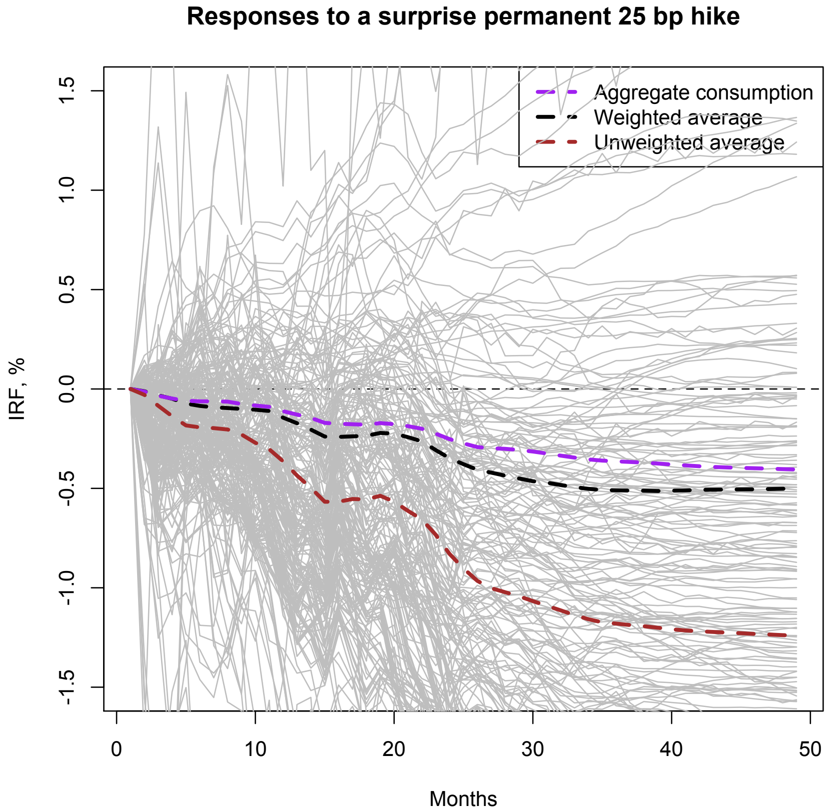


Figure 11: Impulse response decomposition(Detail level, 231 sectors) – SVAR shocks

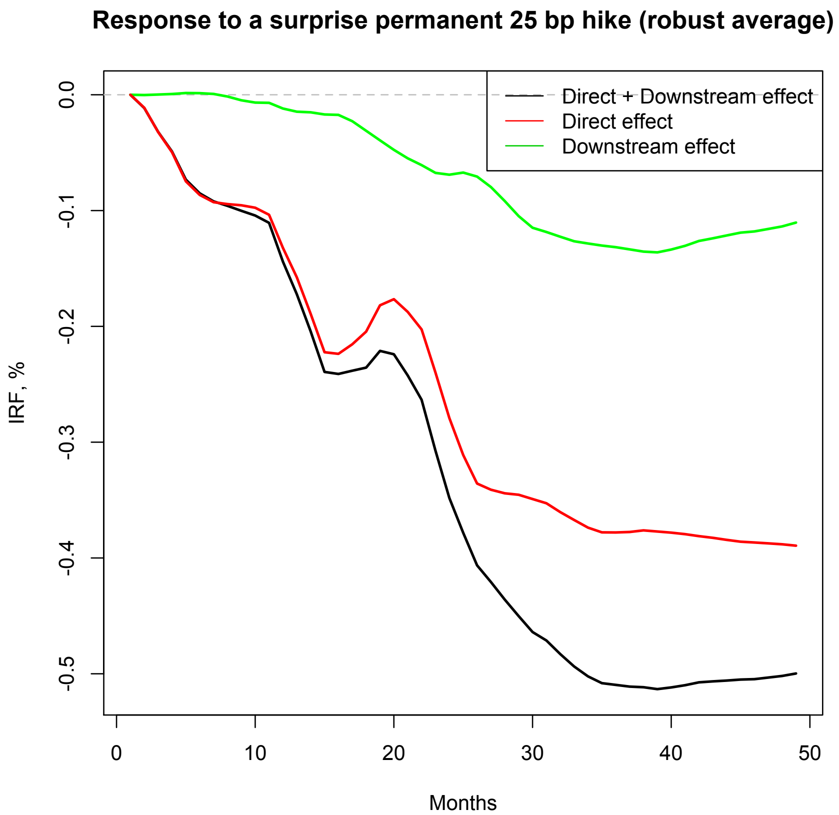


Figure 12: Responses of sectoral consumptions to 25bp tightening (Detail level, 231 sectors) – Event studies shocks

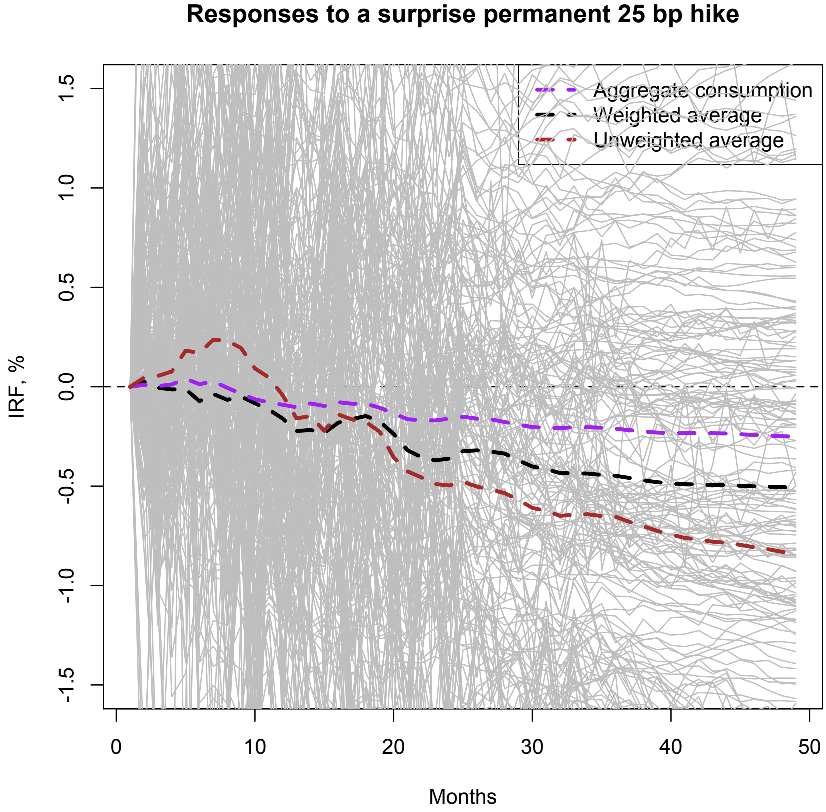
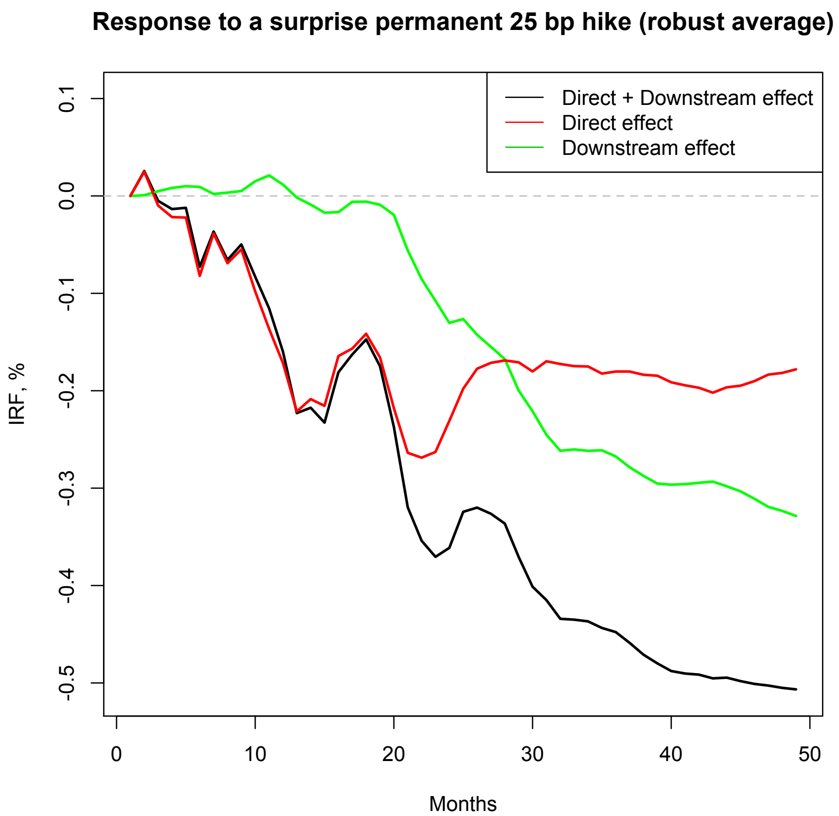


Figure 13: Impulse response decomposition(Detail level, 231 sectors) – Event studies shocks



shocks than the Romer and Romer (2004) shocks.

As for the decomposition, shown in Figure 13, the direct effect only delivers a drop of around 0.27 per cent, so the downstream effect accounts for around 45 per cent at the peak. The downstream effect is coming in with a lag, just as before.

All in all, having additionally considered two alternative monetary policy shocks series, we can see that the downstream effect is between 24 and 45 per cent at the peak, with the SVAR identified shocks at the lower end of the spectrum, event studies shocks at the higher end of the spectrum and Romer and Romer (2004) shocks in the middle. However, despite such variation in the importance of production networks, it still remains at the lower end of the other estimates in the literature. The observed delay in the downstream effect remains robust across the different shock series used.

6.3 Lag specification

As noted by Coibion (2012), unlike the vector autoregression approach, single equation estimation of the effect of monetary policy shocks can be sensitive to the number of lags of monetary policy shocks included. Our baseline specification allowed for 24 lags of monetary policy shocks; in this subsection we examine the robustness of our results to varying the lag length from 12 to 36. Note that results for 14 lags are not reported, as we experienced issues with convergence.

The top chart of Figure 14 shows the peak drop in consumption under full and direct effects under different number of lags of monetary policy shocks. One can see that both effects deliver larger drops for larger lag lengths, although after 24 lags the outcome becomes more stable and in line with our baseline result. As for the contribution of the downstream effect shown in the middle chart, it shows some volatility prior to 22 lags, eventually settling around the 33 per cent mark from the baseline specification and within the a 20 to 40 per cent band, consistent with the results for different monetary policy shocks from the previous subsection.

Recall that in Baseline results section we pointed out to the presence of long-run errors in our impulse responses, where consumption impulse responses do not generally converge back to zero, breaking long-run money neutrality. We also suggested that the presence of such long-run errors coupled with heterogenous peak horizons may inhibit our aggregation procedure. The bottom chart of Figure 14 shows how the long-run errors of full and direct responses obtained by weighted aggregation change with the number of lags. We can see that up until around 24 lags the long-run errors co-move with their respective peak responses. However, as we allow for more lags, the convergence properties of our system improve and the long-run errors start to fall in magnitude, practically reaching zero at 35 lags. Our peak responses and downstream contributions, however show no drastic change as the long-run errors disappear. The above provides some evidence that our results are not driven by the long-run errors.

7 Reconciling "inverted" consumption responses

In this section we show how a slight modification to our original model can reconcile the "inverted" responses of sectoral consumption to monetary policy shocks that we documented in the Results section. Our benchmark model assumed unit elasticity of substitution between consumption from different sectors; if we relax this assumption and instead consider elasticity of substitution equal to $\lambda > 1$, consumption aggregation becomes:

$$C_t = \left[\sum_{k=1}^{K} \omega_{ck}^{\frac{1}{\lambda}} C_{kt}^{1-\frac{1}{\lambda}}\right]^{\frac{\lambda}{\lambda-1}}. \tag{47}$$

Under this assumption goods produced in different sectors becomes closer substitutes. The rest of the model is unchanged, and we can solve it and write down the log-linearised equilibrium around zero-inflation steady state as:

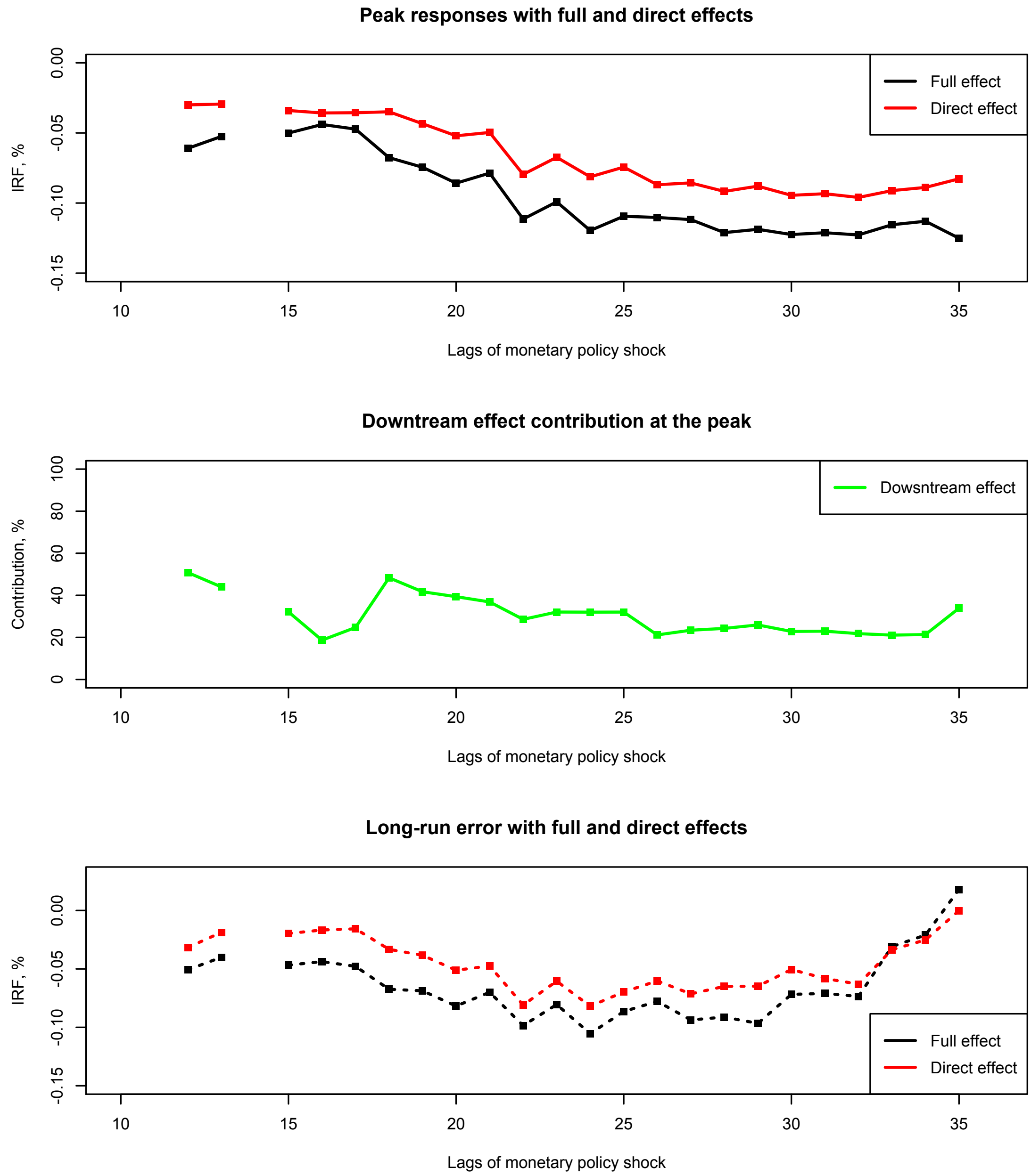
$$p_{kt} = \alpha_k p_{k,t-1} + (1-\alpha_k) p_{kt}^*, \qquad k = 1, 2, ..., K \tag{48}$$

$$p_{kt}^* = (1-\beta\alpha_k) \sum_{j=0}^{\infty} (\beta\alpha_k)^j \mathbb{E}_t mc_{k,t+j}, \qquad k = 1, 2, ..., K \tag{49}$$

$$mc_{kt} = (1-\delta) s_t + \delta \sum_{r=1}^{K} \omega_{kr} p_{rt}, \qquad k = 1, 2, ..., K \tag{50}$$

$$p_t^c + c_t = s_t, \tag{51}$$

Figure 14: Sensitivity of our results to lag specification



Note: Top chart shows peak effects under weighted aggregation of impulse responses to a one-time 25bp tightening under different number of lags of monetary policy shocks included in the specification; middle chart measures the contribution of downstream effect at each number of lags by reporting the difference between full and direct peak effect as a percentage of the former; bottom chart reports the long-run error for each number of lags computed as the value of the weighted aggregate impulse response 100 periods after the one-time 25bp tightening. All estimations are performed using our baseline sample. Results for 14 lags are not reported due to convergence problems.

$$c_{kt} = -\lambda(p_{kt} - p_t^c) + c_t, \qquad k = 1, 2, ..., K \tag{52}$$

$$c_t = \sum_{k=1}^{K} \omega_{ck} c_{kt}, \tag{53}$$

$$s_t = s_{t-1} + r_t, \quad r_t = \rho_r r_{t-1} + \varepsilon_t, \quad \{\varepsilon_t\}_t \sim i.i.d.(0, \sigma_\varepsilon^2). \tag{54}$$

Combining (51) and (52) we obtain the following expression for sectoral consumption:

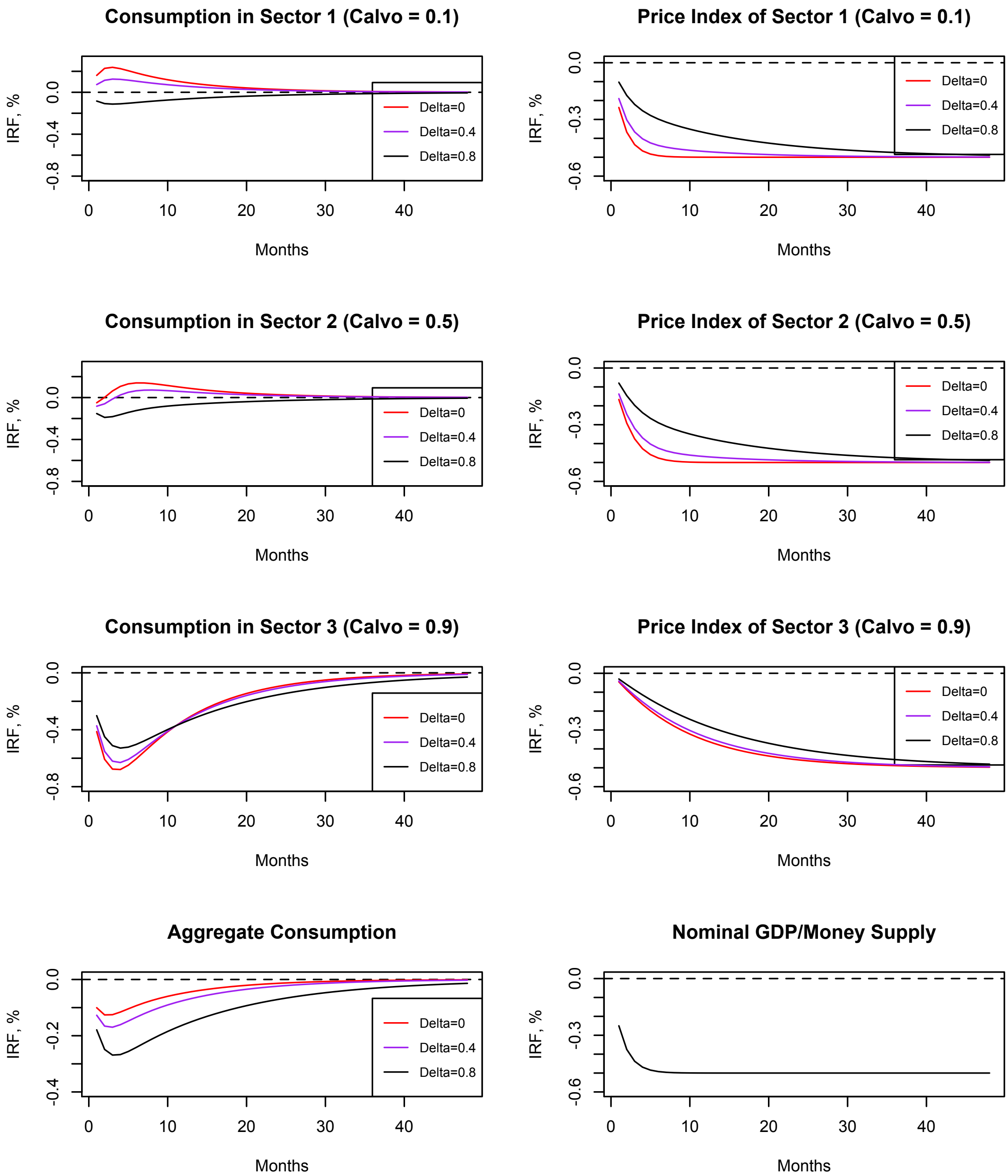
$$c_{kt} = s_t - p_{kt} + (\lambda - 1)(p_t^c - p_{kt}). \tag{55}$$

Under the benchmark case of $\lambda = 1$ we can see that "inverted" responses in consumption are impossible. This is because following a contraction (fall in s_t), sectoral price falls at most as quickly (happens under full flexibility) as s_t, implying a fall in sectoral consumption (and vice versa for an expansion). However, under $\lambda > 1$, "inverted" sectoral consumption responses are possible. For example, consider a monetary contraction and let us focus on the most flexible sector in our economy. Following the contraction, the sectoral price index optimally adjusts downward faster than the overall consumption price index of the economy, so that the second term in (55) becomes positive and possibly outweighs the negative $(s_t - p_{kt})$ term, hence generating a positive sectoral consumption response. Intuitively, firms in flexible industries lower their prices faster than firms in more rigid industries and "steal" customers from the latter. Naturally, we should observe less of this behaviour as the downstream effect becomes stronger as the degree of strategic complementarity in price setting becomes larger, eliminating the relative pricing effects.

To gain further intuition, consider again the three sector ($K = 3$) version of our economy, with calibration just like in the our first exercise in the Model section, with the exception that we set $\lambda = 3$, so that goods produced in different sectors are now stronger substitutes. Figure 15 shows impulse responses to a one-time one standard deviation monetary policy shock that generates a permanent contraction in nominal GDP/money supply.

We can see that in the case with no intermediate inputs ($\delta = 0$) and hence no strategic complementarities in price setting, the most flexible Sector 1 shows an "inverted" response in consumption over the entire horizon, with Sector 2 also

Figure 15: Responses of sectoral consumptions and price indices to a monetary contraction



Note: The figure is constructed by calibrating (48)-(54) for $K = 3$ *and considering a one-time one standard deviation negative innovation to the monetary policy shock variable that generates a permanent contraction in money supply. The impulse responses are found numerically using Dynare.*

having an "inverted" response after 5 months. One can see that this is because they lower their prices much faster than firms in the rigid Sector 3, thus stealing some of the customers of firms in Sector 3. As we increase δ, the extent of "inverted" consumption responses becomes lower, with $\delta = 0.8$ generating no positive consumption responses. This is because higher share of intermediate inputs makes the degree of complementarity in price setting higher, as firms' marginal costs are more sensitive to their suppliers' prices, making the timing of price changing more uniform across sectors. Note that the move from $\delta = 0$ to $\delta = 0.4$ corresponds to a negative contribution of downstream effect in framework we developed in the empirical sections.

Interestingly, although higher δ makes the consumption response more negative for the more flexible Sectors 1 and 2, the magnitude of peak drop in consumption for the rigid Sector 3 falls for higher shares for intermediate inputs. Hence, for Sector 3 the downstream effect does not lead to amplification, but rather to a contraction of the consumption response. Again, the latter corresponds to negative contribution of the downstream effect in our earlier notation.

The latter set of observations generates two potentially very interesting testable hypotheses. Firstly, one could test whether "inverted" consumption responses are more prevalent among the more flexible sectors. Secondly, one could test whether downstream effect leads to a contraction in magnitude of "correctly signed" peak consumption response for the more rigid sectors. We leave the above exercises for future research.

Finally, we can also find an analytical solution for sectoral consumption for the case with myopic firms that fully discount the future when deciding on the optimal price, so that $p^*_{kt} = mc_{kt}, \forall k$. Following a procedure identical to the one in the Model section, the expression for sectoral consumption is given by:

$$c_{kt} = \alpha_k c_{k,t-1} + \mu_k s_t - \alpha_k s_{t-1} + (1-\alpha_k)\delta \sum_{r=1}^{K} \omega_{kr} c_{rt} + \kappa_k p^c_t - (\lambda - 1)\alpha_k p^c_{t-1} \quad (56)$$

where $\mu_k \equiv \frac{\lambda(1-(1-\alpha_k)\delta)-(1-\alpha_k)(1-\delta)}{\lambda}$ and $\kappa_k \equiv (\lambda-1)(1-(1-\alpha_k)\delta), k = 1, 2, ..., K$.

As we can see, for $\lambda = 1$ the above collapses to the sectoral consumption expression (39) found earlier. Estimating an empirical counterpart of the above equation and finding full and restricted impulse responses to a monetary policy shock is slightly more involved in this case, however. In particular, it additionally requires finding a full and restricted impulse response for the consumption price index p_t^c which is beyond the scope of this paper. However, it is certainly an interesting avenue for future work. Indeed, if one could collect sectoral price data that could be matched to definitions used in BEA IO Accounts, one could run a regression similar to the one with ran for consumption:

$$\Delta p_{kt} = \eta_{k0}^p + \sum_{j=1}^{12} \eta_{kj}^p \Delta p_{k,t-j} + \sum_{j=1}^{24} \phi_{kj}^p r_{t-j} + \sum_{j=1}^{12} \psi_{kj}^p \sum_{r=1}^{K} \omega_{kr} \Delta p_{r,t-j} + \epsilon_{kt}^p, \tag{57}$$

$k = 1, 2, ..., K; t = 1, 2, ..., T$; where p_{kt} is log sectoral price index for sector k. One could then run full and restricted impulse responses, and perform weighted aggregation given by $p_t^c = \sum_{k=1}^{K} \omega_{ck} p_{kt}$ to find the full and restricted impulse response for the consumption price index.

Note that the full and restricted impulse responses for sectoral prices estimated in this way would also be interesting in their own right. If one wanted to calibrate the sector specific Calvo parameters $\{\alpha_k\}_{k=1}^{K}$, the most natural way to estimate those would be to look at the speed of adjustment in the *restricted* impulse responses of the corresponding sectoral prices. In contrast, the speed of adjustment in the full impulse response is determined by a mixture of the sector's own Calvo parameter and the Calvo parameters of its suppliers.

8 Conclusion and future extensions

A large theoretical literature outlining the way in which production networks create complementarities in price setting and thus amplify the effect of monetary policy shocks exists. However, there has been hardly any empirical assessment of the above mechanism. In this paper we make a first step towards filling this large gap in the literature. In particular, we offer novel empirical evidence that 20 to 45 per cent of the effect of monetary policy shocks on US consumption comes from the amplification through input-output linkages. In addition, we observe that the effect of production networks comes in with a delay of around 18 months. Our results appear to be robust to different levels of sectoral aggregation, different monetary policy shock series and different lag specifications.

Our approach still has limitations that create space for future research. Firstly, we have seen that the model we use to build intuition and motivate our econometric specification cannot explain the observed positive consumption responses to a monetary tightening. The slight modification to our model that can reconcile such "inverted" responses delivers an econometric specification that additionally requires modelling the contribution of production networks to the adjustment dynamics of the consumption price index. We outline how the latter can be done and it shall be our most immediate research agenda. In addition, we have also shown that as a by-product of the above procedure one can obtain the empirical dynamics of sectoral prices' adjustment that has been isolated from the influence of suppliers' prices. We then explain that the latter can be used to calibrate sector-specific Calvo parameters in New Keynesian models with intermediate inputs.

Secondly, we observe large heterogeneity in sectoral consumption responses to a monetary policy shock and a parallel research agenda would be to study the determinants of such differential responses. Our theoretical framework generates a number of predictions regarding the latter – for example, "inverted" consumption responses are attributed to the more flexible sectors, whereas production networks are predicted to make the more rigid sectors experience a drop in the magnitude of their peak consumption response. Testing the above predictions would be a fruitful research programme.

Finally, in this paper we have considered production network effects that travel downstream, or from suppliers to customers. An interesting extension of our work would be to provide an empirical assessment of production network effects that travel upstream.

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Appendix A Model with Taylor rule

A.1 Equilibrium conditions

Consider an arguably more realistic setting, where we model the monetary authority as setting the level of nominal interest I_t in the economy. The latter evolves according to the following version of a Taylor interest rate rule:

$$I_t = \frac{1}{\beta}\left(\frac{P_t^c}{P_{t-1}^c}\right)^{\varphi_\pi}\left(\frac{C_t}{C}\right)^{\varphi_c} e^{r_t}, \tag{58}$$

where $r_t = \rho_r r_{t-1} + \varepsilon_t$ is a monetary policy shock following an AR(1) process with the innovations $\{\varepsilon_t\}_t$ constituting a zero-mean white noise process with variance σ_ε^2; C is the steady-state level of consumption. As we can see, the nominal interest rate reacts to consumption price index inflation and deviations of consumption from its steady state, with the sensitivities represented by the parameters φ_π and φ_c respectively. Note that aggregate consumption and not aggregate output appears in the Taylor rule, as it is the former that represents real gross value added, or real GDP, in our model.

The only adjustment we need to make to our original model to incorporate the nominal interest rate concerns the representative household's problem. In particular, now households are allowed to purchase one period bonds D_t that pay a nominal gross interest rate of I_t and are in zero net supply. The representative household's decision problem is now given by:

$$\max_{\{C_t,L_t,D_t\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \gamma L_t\right) \tag{59}$$

subject to

$$P_t^c C_t + D_t \leq I_{t-1} D_{t-1} + W_t L_t + \sum_{k=1}^{K} \Pi_{kt}, \tag{60}$$

where C_t and P_t^c are the composite consumption good and the consumption price index respectively, L_t is labour supply, D_t represents bonds purchased in period t that mature in period $(t+1)$ and Π_{kt} denotes aggregate nominal profits of firms in sector k; β is the discount factor for future utility and γ is a parameter capturing the relative disutility of labour.

The first order condition of the above problem are standard, namely, an Euler equation for consumption:

$$C_t^{-1} = \beta \mathbb{E}_t \left[C_{t+1}^{-1} \frac{I_t}{P_{t+1}^c} P_t^c \right] \tag{61}$$

and an equation for consumption-labour supply choice:

$$C_t^{-1} = \gamma \frac{P_t^c}{W_t}. \tag{62}$$

All other optimality and market clearing conditions remain unchanged from our original model.

A.2 Log-linearised equilibrium

Log-linearising our new equilibrium conditions around the symmetric zero-inflation steady state, we obtain the following system in terms of economic variables of interest (lower case letters denote log-deviations from the steady state):

$$p_{kt} = \alpha_k p_{k,t-1} + (1-\alpha_k) p_{kt}^*, \qquad k = 1, 2, ..., K \tag{63}$$

$$p_{kt}^* = (1-\beta\alpha_k) \sum_{j=0}^{\infty} (\beta\alpha_k)^j \mathbb{E}_t mc_{k,t+j}, \qquad k = 1, 2, ..., K \tag{64}$$

$$mc_{kt} = (1-\delta) w_t + \delta \sum_{r=1}^{K} \omega_{kr} p_{rt}, \qquad k = 1, 2, ..., K \tag{65}$$

$$p_t^c + c_t = w_t, \tag{66}$$

$$c_t = \mathbb{E}_t[c_{t+1}] - (i_t - (\mathbb{E}_t[p_{t+1}^c] - p_t^c)), \tag{67}$$

$$c_{kt} = -p_{kt} + p_t^c + c_t, \qquad k = 1, 2, ..., K \tag{68}$$

$$c_t = \sum_{k=1}^{K} \omega_{ck} c_{kt}, \tag{69}$$

$$i_t = \varphi_\pi (p_t^c - p_{t-1}^c) + \varphi_c c_t + r_t, \tag{70}$$

$$r_t = \rho_r r_{t-1} + \varepsilon_t, \quad \{\varepsilon_t\}_t \sim i.i.d.(0, \sigma_\varepsilon^2). \tag{71}$$

As we can see, the equations (63)-(65) responsible for the price setting of firms remain unchanged from our original model. Therefore, the mechanisms generating complementarities in price setting under $\delta > 0$ remain in place. Equation (67) is the log-linearised Euler equation that is new compared to our original model. One can from (64) how the more persistent price adjustment following a monetary policy shock introduced by production networks translates to more gradual adjustment of the real interest rate ($i_t - (\mathbb{E}_t[p^c_{t+1}] - p^c_t)$). The latter amplifies the short-run effect of monetary policy shocks on consumption.

As before, one cannot easily find an analytical solution to the above system due to the asymmetries in our model. Instead, in the next subsection we consider our model in the context of the three sector ($K = 3$) economy introduced earlier, and consider numerically computed impulse responses to a monetary policy shock.

A.3 Three-sector economy example $(K = 3)$

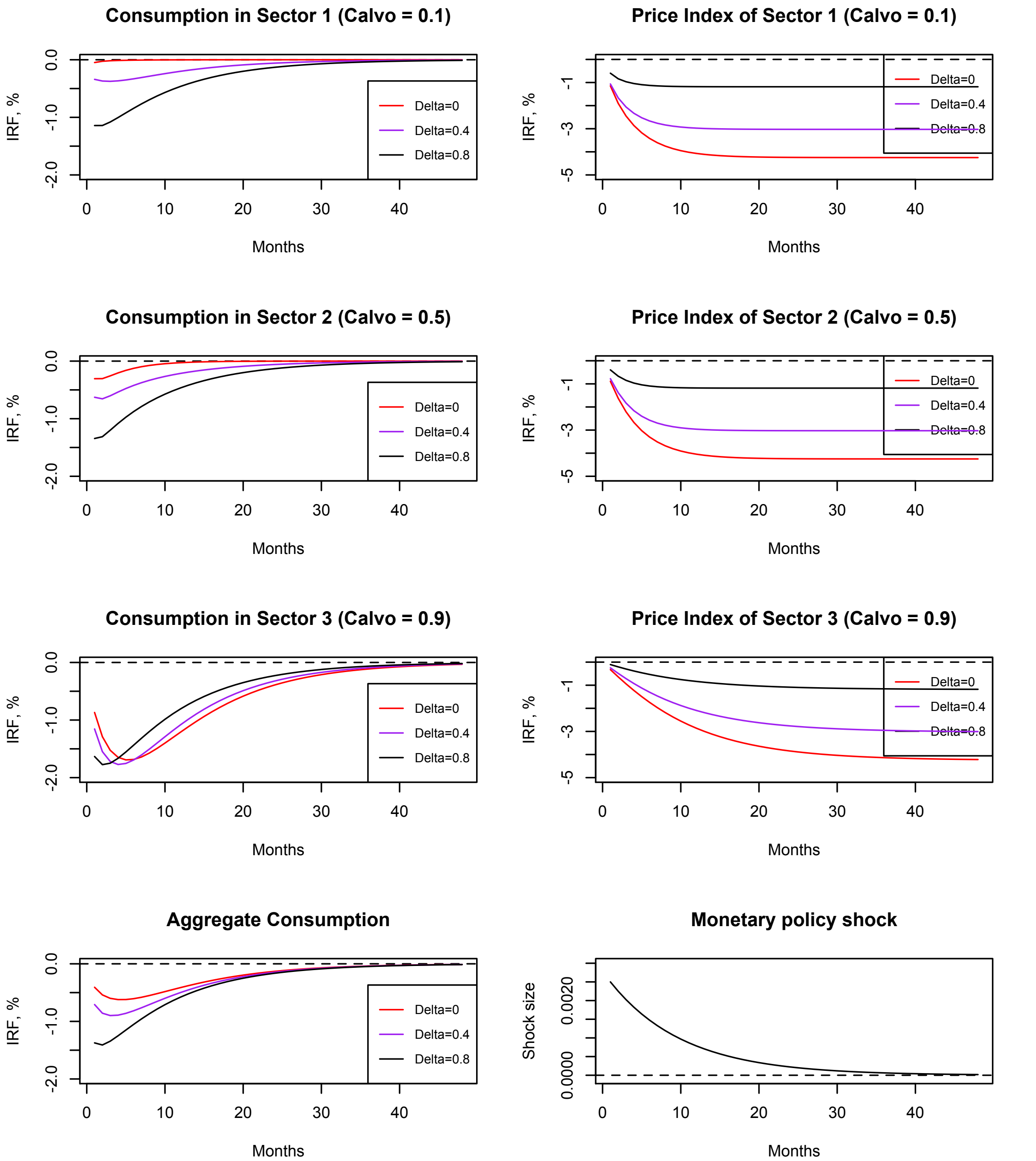
Here we focus on a three-sector ($K = 3$) version of our economy and perform two exercises that consider the response of our system to a monetary contraction. In particular, we subject our system to a one-time one-standard deviation positive innovation to the monetary policy shock r that generates a monetary tightening. We calibrate our model to monthly data by setting $\beta = 0.9975, \rho_r = 0.9, \sigma_\varepsilon = 0.0025, \varphi_\pi = 1.24$ and φ_c=0.33/12.

Just like for the original model, in our first exercise Sector 1 is assumed to be almost, but not completely flexible, ($\alpha_1 = 0.1$), Sector 2 is semi-flexible ($\alpha_2 = 0.5$ and Sector 3 is almost completely rigid ($\alpha_3 = 0.9$). The input-output matrix is set to be completely symmetric, so that $\omega_{kr} = 1/3 \quad \forall k, r \in \{1, 2, 3\}$. Figure 16 shows the responses of our system to the monetary contraction for different values of $\delta \in \{0, 0.4, 0.8\}$. As one can see, the results are qualitatively identical to those obtained under money supply rule in our original model. Firstly, as before, under $\delta = 0$, the magnitude of contraction in sectoral consumption increases in sector's own price stickiness. Secondly, just like in the original model, for $\delta > 0$, the amplification of the consumption response due to production networks is greater for the more flexible sectors. Thirdly, other things equal, the degree of amplification increases in δ.

In our second exercise, we assume that Sector 1 is completely flexible ($\alpha_1 = 0$), with the other sectors remaining unchanged from the previous exercise ($\alpha_2 = 0.5, \alpha_3 = 0.9$). Just as before, firms in Sector 1 buy inputs only from other firms in Sector 1 ($\omega_{11} = 1, \omega_{12} = \omega_{13} = 0$), whereas the input-output weights for the other two sectors are as in the previous exercise ($\omega_{kr} = 1/3, \quad \forall k, r \in \{2, 3\}$). Figure 17 shows the response of such a system to a monetary contraction. We can see that, just as with the money supply rule in the original model, Sector 1 does not experience any change in consumption under $\delta = 0$, with $\delta > 0$ leaving the zero consumption response in place due to the fact that the propagation of price stickiness still goes downstream. As before, since firms in Sector 1 do not purchase any inputs from firms in sticky sectors 2 and 3, the do not inherit any stickiness.

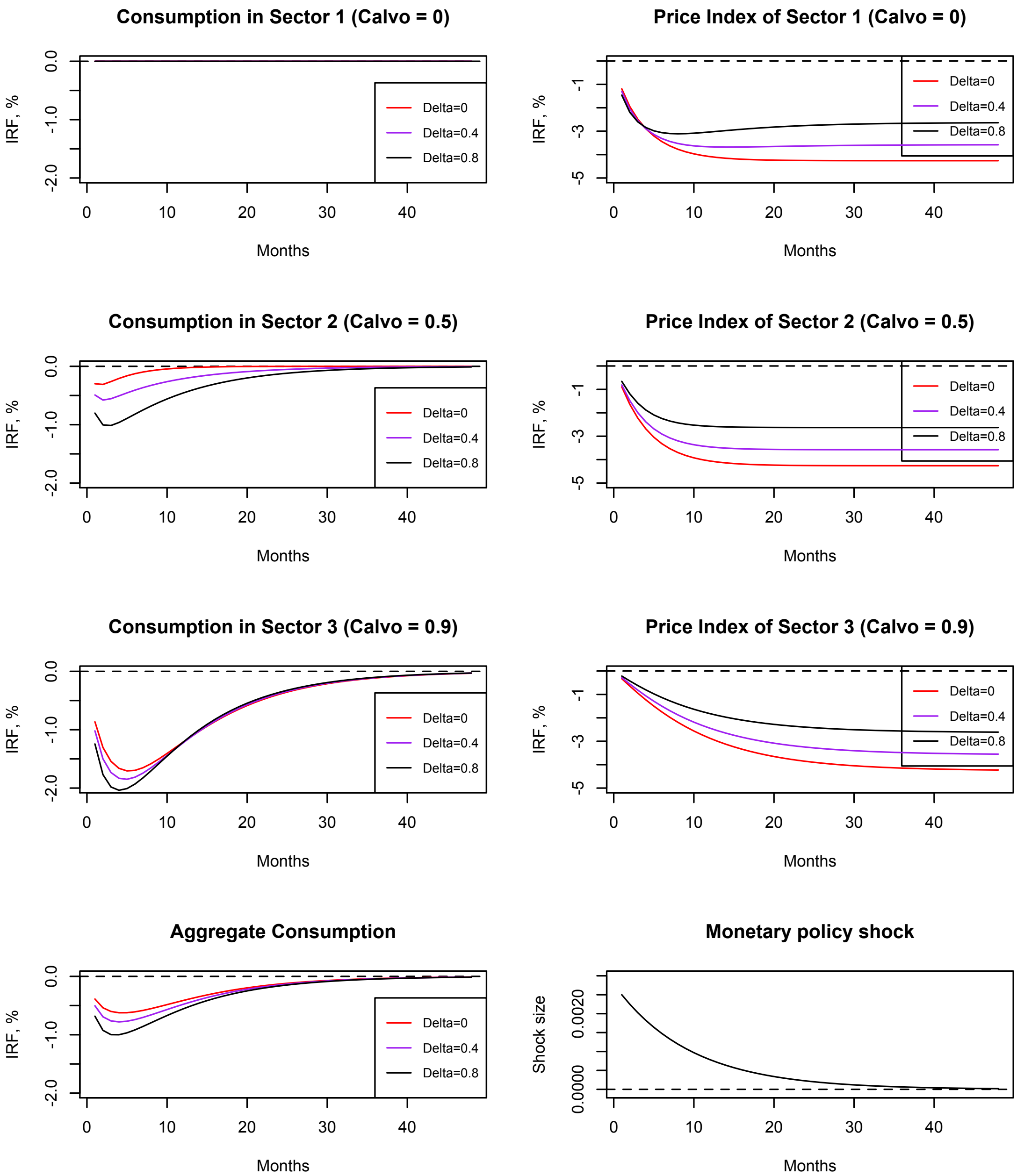
Finally, in Section 7 we consider a modified version of our original model, where we relax the assumption of unit elasticity of substitution across sectoral consumptions and allow it to be equal to $\lambda > 1$. As we have seen, in case of money supply rule in our original model, it allowed us to account for the empirically observed "inverted" consumption responses, where some sectoral consumption increase following a monetary tightening. Here we would like to test whether such property would also be preserved under the Taylor rule specification for monetary policy. In Figure 18 we consider a monetary tightening for calibration identical to that in our first exercise, with the exception that elasticity of substitution across sectoral consumptions is set to $\lambda = 3$. As we can see, for $\delta = 0$ and $\delta = 0.4$ the more flexible sectors 1 and 2 indeed exhibit "inverted" consumption responses, whereas for $\delta = 0.8$ all "inverted" responses are eliminated. Hence, in this respect, our model with Taylor rule behaves just like the original one with money supply rule. In addition, just as in the original model. we can observe that the magnitude of peak drop in consumption for the most rigid Sector 3 falls for higher values of δ.

Figure 16: Responses of sectoral consumptions and prices to a monetary policy shocks (Taylor rule)



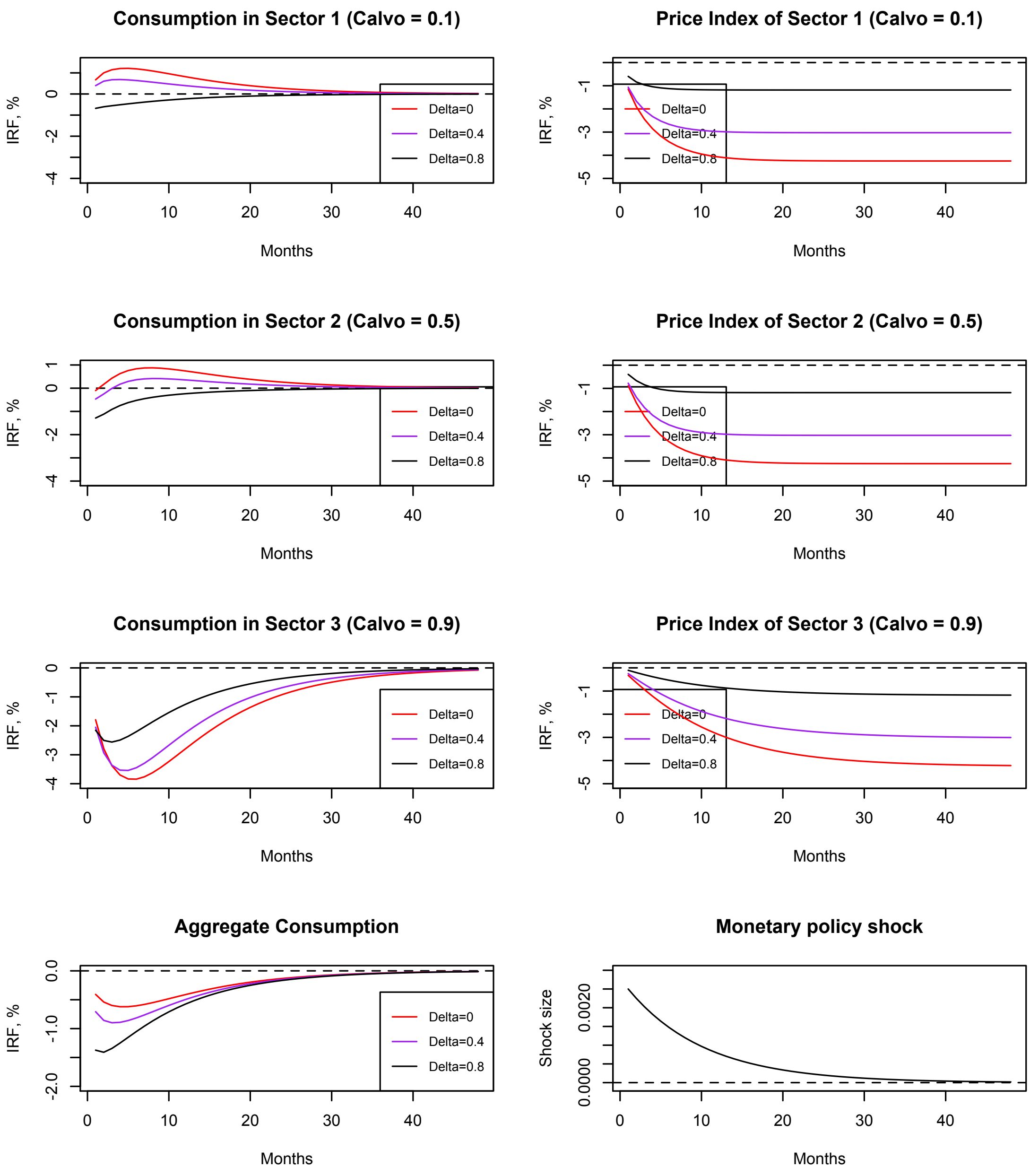
Note: The figure is constructed by calibrating (63)-(71) for $K = 3$ and considering a one-time one standard deviation positive innovation to the monetary policy shock variable that generates a monetary contraction. The impulse responses are found numerically using Dynare.

Figure 17: Responses of sectoral consumptions and prices to a monetary policy shocks (Taylor rule)



Note: The figure is constructed by calibrating (63)-(71) for $K = 3$ and considering a one-time one standard deviation positive innovation to the monetary policy shock variable that generates a monetary contraction. The impulse responses are found numerically using Dynare.

Figure 18: Responses of sectoral consumptions and prices to a monetary policy shocks (Taylor rule)



Note: The figure is constructed by calibrating (63)-(71) for $K = 3$ and considering a one-time one standard deviation positive innovation to the monetary policy shock variable that generates a monetary contraction. The impulse responses are found numerically using Dynare.

Appendix B Model steady state

Just as in Carvalho and Lee (2011) and Pasten et al. (2016), we are looking for a zero-inflation steady state that is also symmetric in the sense that:

$$Y_{kj} = Y, \quad L_{kj} = L, \quad Z_{kj} = Z, \quad P_{kj} = P, \quad \forall k, j \tag{72}$$

in steady state. Not that there is no price stickiness in steady state, so the actual price set equals the optimal price. Given that in such steady state all firms set the same prices, our sectoral, inputs and consumption price indices are all equal in steady state:

$$P^c = P^k = P_k = P, \quad \forall k. \tag{73}$$

We can write steady state expressions for the consumption-labour choice, representative households' budget constraint, firm's profits, firm production function, optimal inputs mix condition and price as a mark-up over the nominal marginal cost as:

$$\frac{W}{P} = C, \tag{74}$$

$$PC = WL + \Pi, \tag{75}$$

$$\Pi = PY - WL - PZ, \tag{76}$$

$$Y = L^{1-\delta} Z^{\delta}, \tag{77}$$

$$\delta WL = (1-\delta) PZ, \tag{78}$$

$$P = \frac{\theta}{\theta - 1} MC = \frac{\theta}{\theta - 1} \left(\frac{1}{1-\delta} \right) \left(\frac{\delta}{1-\delta} \right)^{-\delta} W^{1-\delta} P^{\delta}. \tag{79}$$

From (79) we get that:

$$\frac{W}{P} = \left(\frac{\theta - 1}{\theta \bar{\delta}} \right)^{\frac{1}{1-\delta}}, \tag{80}$$

where $\bar{\delta} \equiv \left(\frac{1}{1-\delta}\right)\left(\frac{\delta}{1-\delta}\right)^{-\delta}$. From (79) we can express Z as:

$$Z = \frac{\delta}{1-\delta} \frac{W}{P} L. \tag{81}$$

Plugging (81) into (77):

$$Y = L \left(\frac{\delta}{1-\delta} \right)^{\delta} \left(\frac{W}{P} \right)^{\delta}. \tag{82}$$

From (81) and (82) we can express L and Z in terms of Y and plug into (76):

$$\Pi = PY - W \left(\frac{\delta}{1-\delta} \right)^{-\delta} \left(\frac{W}{P} \right)^{\delta} Y - \left(\frac{\delta}{1-\delta} \right) W \left(\frac{\delta}{1-\delta} \right)^{-\delta} \left(\frac{W}{P} \right)^{\delta} Y, \tag{83}$$

$$\frac{\Pi}{P} = Y - \left(\frac{1}{1-\delta}\right)\left(\frac{\delta}{1-\delta}\right)^{-\delta}\left(\frac{W}{P}\right)^{1-\delta} Y. \tag{84}$$

Given the definition of $\bar{\delta}$ and (80), the expression in (84) implies that:

$$\frac{\Pi}{P} = \frac{1}{\theta}Y. \tag{85}$$

Insert (85) into (76) and use (81):

$$\frac{1}{\theta}PY = PY - WL - PZ, \tag{86}$$

$$\frac{\theta-1}{\theta}PY = \frac{1}{1-\delta}WL. \tag{87}$$

Now combine (75) with (87) to obtain:

$$C = \left[1 - \frac{\delta(\theta-1)}{\theta}\right] Y. \tag{88}$$

Similarly, combine (87) and (80) to obtain:

$$L = \left[\delta\left(\frac{\theta-1}{\theta}\right)\right]^{-\frac{\delta}{1-\delta}} Y. \tag{89}$$

Inserting (89) into (81) yields the following expression for Z:

$$Z = \delta\left(\frac{\theta-1}{\theta}\right) Y. \tag{90}$$

Finally, (74) and (88) give us expression for Y:

$$Y = \left[1 - \frac{\delta(\theta-1)}{\theta}\right]^{-1}\left(\frac{\theta-1}{\theta\bar{\delta}}\right)^{\frac{1}{1-\delta}}. \tag{91}$$

Overall, (80), (85), (88), (89), (90) and (91) define steady state for $\{C, L, Z, Y, \frac{W}{P}, \frac{\Pi}{P}\}$.

Given the conditions in (4) and (19) we can also find expressions for steady state sectoral inputs use:

$$Z_{kj}(r) = \omega_{kr} Z, \quad \forall j, k, r \tag{92}$$

and sectoral consumption:

$$C_k = \omega_{ck} C, \quad \forall k. \tag{93}$$

One could also show that in steady state the measure of firms in sector k, f_k is determined by a combination of consumption shares $\{\omega_{ck}\}_{k=1}^{K}$ and the input-output weights $\{\omega_{kr}\}_{k,r}$. The latter would allow us to find steady state expressions for firm-level consumption and inputs use. However, as the latter variables are not of our interest, we shall omit such proof here.

Appendix C List of sectors used

The definition of sectors here follows that used by the US Bureau of Economic Analysis (BEA) in their Input-Output accounts. The figures in parentheses are shares of corresponding real final sectoral consumption in aggregate real personal consumption expenditure (expressed in per cent). The consumption shares are constructed using the 2007 Use Tables for Detail and Summary accounts.

C.1 Detail level (231 sectors)

1. Abrasive product manufacturing (0.0015)
2. Accommodation (0.978)
3. Accounting, tax preparation, bookkeeping, and payroll services (0.1578)
4. Adhesive manufacturing (0.0098)
5. Air transportation (0.8477)
6. All other chemical product and preparation manufacturing (0.0221)
7. All other converted paper product manufacturing (0.008)
8. All other food and drinking places (0.7035)
9. All other food manufacturing (0.1484)
10. All other miscellaneous electrical equipment and component manufacturing (0.0029)
11. All other miscellaneous manufacturing (0.1549)
12. All other transportation equipment manufacturing (0.0464)
13. All other wood product manufacturing (0.037)
14. Ammunition, arms, ordnance, and accessories manufacturing (0.035)
15. Amusement parks and arcades (0.1208)
16. Animal (except poultry) slaughtering, rendering, and processing (0.5645)
17. Apparel manufacturing (1.0472)
18. Automobile manufacturing (0.6824)
19. Automotive equipment rental and leasing (0.5097)
20. Automotive repair and maintenance (1.5915)
21. Boat building (0.0777)
22. Book publishers (0.2055)

23. Bread and bakery product manufacturing (0.375)

24. Breakfast cereal manufacturing (0.0814)

25. Breweries (0.2463)

26. Carpet and rug mills (0.0796)

27. Cheese manufacturing (0.1196)

28. Child day care services (0.4267)

29. Civic, social, professional, and similar organizations (0.3918)

30. Clay product and refractory manufacturing (0.0232)

31. Coffee and tea manufacturing (0.0463)

32. Commercial and industrial machinery and equipment rental and leasing (0.0038)

33. Community food, housing, and other relief services, including rehabilitation services (0.3497)

34. Computer terminals and other computer peripheral equipment manufacturing (0.1281)

35. Consumer goods and general rental centers (0.2629)

36. Cookie, cracker, pasta, and tortilla manufacturing (0.1838)

37. Couriers and messengers (0.0171)

38. Crown and closure manufacturing and metal stamping (0.0051)

39. Curtain and linen mills (0.1163)

40. Cut stone and stone product manufacturing (0.0368)

41. Cutlery and handtool manufacturing (0.0523)

42. Dairy cattle and milk production (0.0018)

43. Death care services (0.186)

44. Directory, mailing list, and other publishers (0.0757)

45. Distilleries (0.0958)

46. Dog and cat food manufacturing (0.1287)

47. Doll, toy, and game manufacturing (0.2009)

48. Dry-cleaning and laundry services (0.1325)

49. Dry, condensed, and evaporated dairy product manufacturing (0.0678)

50. Electric lamp bulb and part manufacturing (0.0129)

51. Electric power generation, transmission, and distribution (1.5208)

52. Electromedical and electrotherapeutic apparatus manufacturing (0.0214)

53. Electronic and precision equipment repair and maintenance (0.0413)
54. Elementary and secondary schools (0.3968)
55. Employment services (0.0155)
56. Fabric mills (0.0149)
57. Fertilizer manufacturing (0.0024)
58. Fiber, yarn, and thread mills (0.0011)
59. Fishing, hunting and trapping (0.0539)
60. Flavoring syrup and concentrate manufacturing (0.0024)
61. Flour milling and malt manufacturing (0.03)
62. Fluid milk and butter manufacturing (0.2024)
63. Frozen food manufacturing (0.2101)
64. Fruit and tree nut farming (0.1467)
65. Fruit and vegetable canning, pickling, and drying (0.2501)
66. Full-service restaurants (1.8692)
67. Funds, trusts, and other financial vehicles (1.272)
68. Gambling industries (except casino hotels) (0.8798)
69. Glass and glass product manufacturing (0.031)
70. Grain farming (0.0112)
71. Grantmaking, giving, and social advocacy organizations (0.4099)
72. Ground or treated mineral and earth manufacturing (0.0014)
73. Hardware manufacturing (0.0045)
74. Heating equipment (except warm air furnaces) manufacturing (0.0175)
75. Home health care services (0.6655)
76. Hospitals (6.6646)
77. Household cooking appliance manufacturing (0.0543)
78. Household laundry equipment manufacturing (0.051)
79. Household refrigerator and home freezer manufacturing (0.0507)
80. Housing (15.1663)
81. Ice cream and frozen dessert manufacturing (0.0283)
82. Independent artists, writers, and performers (0.001)
83. Individual and family services (0.5993)
84. Industrial gas manufacturing (0.0006)

85. Institutional furniture manufacturing (0.0004)
86. Insurance carriers (2.9552)
87. Internet publishing and broadcasting and Web search portals (0.0292)
88. Investigation and security services (0.0787)
89. Iron and steel mills and ferroalloy manufacturing (0.0003)
90. Junior colleges, colleges, universities, and professional schools (1.6815)
91. Lawn and garden equipment manufacturing (0.0083)
92. Leather and allied product manufacturing (0.3449)
93. Legal services (0.9264)
94. Light truck and utility vehicle manufacturing (1.1916)
95. Lighting fixture manufacturing (0.0213)
96. Lime and gypsum product manufacturing (0.0002)
97. Limited-service restaurants (2.4644)
98. Manufacturing and reproducing magnetic and optical media (0.0078)
99. Medical and diagnostic laboratories (0.2954)
100. Metal can, box, and other metal container (light gauge) manufacturing (0.0013)
101. Metal cutting and forming machine tool manufacturing (0.0007)
102. Monetary authorities and depository credit intermediation (1.7624)
103. Motor and generator manufacturing (0.0012)
104. Motor home manufacturing (0.052)
105. Motor vehicle electrical and electronic equipment manufacturing (0.0296)
106. Motor vehicle gasoline engine and engine parts manufacturing (0.0154)
107. Motor vehicle seating and interior trim manufacturing (0.0001)
108. Motor vehicle steering, suspension component (except spring), and brake systems manufacturing (0.0113)
109. Motor vehicle transmission and power train parts manufacturing (0.0177)
110. Museums, historical sites, zoos, and parks (0.1255)
111. Natural gas distribution (0.6334)
112. News syndicates, libraries, archives and all other information services (0.0344)
113. Newspaper publishers (0.1007)
114. Nonferrous metal foundries (0.002)
115. Nonupholstered wood household furniture manufacturing (0.1659)

116. Nursing and community care facilities (1.3948)

117. Office furniture and custom architectural woodwork and millwork manufacturing (0.0017)

118. Office machinery manufacturing (0.0031)

119. Office supplies (except paper) manufacturing (0.0263)

120. Offices of dentists (0.9947)

121. Offices of other health practitioners (0.6282)

122. Offices of physicians (3.5541)

123. Ophthalmic goods manufacturing (0.0755)

124. Optical instrument and lens manufacturing (0.0002)

125. Other ambulatory health care services (0.2609)

126. Other amusement and recreation industries (0.5017)

127. Other animal food manufacturing (0.0185)

128. Other basic inorganic chemical manufacturing (0.0002)

129. Other communications equipment manufacturing (0.0004)

130. Other concrete product manufacturing (0.0002)

131. Other crop farming (0.0027)

132. Other educational services (0.4976)

133. Other electronic component manufacturing (0.0039)

134. Other fabricated metal manufacturing (0.0221)

135. Other financial investment activities (1.1098)

136. Other furniture related product manufacturing (0.0961)

137. Other general purpose machinery manufacturing (0.0028)

138. Other household nonupholstered furniture (0.0571)

139. Other industrial machinery manufacturing (0.0044)

140. Other major household appliance manufacturing (0.0141)

141. Other motor vehicle parts manufacturing (0.0445)

142. Other nonmetallic mineral mining and quarrying (0.0009)

143. Other personal services (0.5068)

144. Other petroleum and coal products manufacturing (0.0507)

145. Other plastics product manufacturing (0.1036)

146. Other real estate (0.0421)

147. Other rubber product manufacturing (0.0113)

148. Other state and local government enterprises (0.5191)

149. Other support services (0.0034)

150. Other textile product mills (0.0409)

151. Outpatient care centers (0.8113)

152. Paint and coating manufacturing (0.0033)

153. Paper bag and coated and treated paper manufacturing (0.0123)

154. Paper mills (0.133)

155. Paperboard container manufacturing (0.0053)

156. Periodical Publishers (0.1348)

157. Personal and household goods repair and maintenance (0.1735)

158. Personal care services (0.6029)

159. Pesticide and other agricultural chemical manufacturing (0.0315)

160. Petroleum refineries (2.1673)

161. Pharmaceutical preparation manufacturing (1.6621)

162. Photographic and photocopying equipment manufacturing (0.008)

163. Photographic services (0.0747)

164. Plastics packaging materials and unlaminated film and sheet manufacturing (0.028)

165. Plate work and fabricated structural product manufacturing (0.0008)

166. Polystyrene foam product manufacturing (0.0063)

167. Postal service (0.1016)

168. Poultry and egg production (0.043)

169. Poultry processing (0.2914)

170. Power-driven handtool manufacturing (0.0207)

171. Power, distribution, and specialty transformer manufacturing (0)

172. Primary battery manufacturing (0.0254)

173. Printed circuit assembly (electronic assembly) manufacturing (0.0017)

174. Printing (0.0253)

175. Promoters of performing arts and sports and agents for public figures (0.0908)

176. Radio and television broadcasting (0.0465)

177. Rail transportation (0.067)

178. Religious organizations (0.7925)

179. Residential mental retardation, mental health, substance abuse and other facilities (0.3514)

180. Rubber and plastics hoses and belting manufacturing (0.0043)

181. Sanitary paper product manufacturing (0.0565)

182. Satellite, telecommunications resellers, and all other telecommunications (0.1124)

183. Scenic and sightseeing transportation and support activities for transportation (0.0963)

184. Scientific research and development services (0.0475)

185. Seafood product preparation and packaging (0.0459)

186. Search, detection, and navigation instruments manufacturing (0.0003)

187. Seasoning and dressing manufacturing (0.0933)

188. Services to buildings and dwellings (0.1561)

189. Showcase, partition, shelving, and locker manufacturing (0.006)

190. Small electrical appliance manufacturing (0.0957)

191. Snack food manufacturing (0.2059)

192. Soap and cleaning compound manufacturing (0.2399)

193. Soft drink and ice manufacturing (0.4019)

194. Software publishers (0.2686)

195. Sound recording industries (0.0853)

196. Soybean and other oilseed processing (0.0076)

197. Specialized design services (0.0454)

198. Sporting and athletic goods manufacturing (0.14)

199. Spring and wire product manufacturing (0.0009)

200. Stationery product manufacturing (0.0077)

201. Steel product manufacturing from purchased steel (0.0047)

202. Storage battery manufacturing (0.0199)

203. Sugar and confectionery product manufacturing (0.2039)

204. Support activities for agriculture and forestry (0.0016)

205. Surgical and medical instrument manufacturing (0.0019)

206. Surgical appliance and supplies manufacturing (0.081)

207. Switchgear and switchboard apparatus manufacturing (0.0011)

208. Telephone apparatus manufacturing (0.0064)

209. Textile and fabric finishing and fabric coating mills (0.0039)

210. Tire manufacturing (0.1015)

211. Tobacco product manufacturing (0.4653)

212. Toilet preparation manufacturing (0.3328)

213. Transit and ground passenger transportation (0.2913)

214. Travel arrangement and reservation services (0.147)

215. Travel trailer and camper manufacturing (0.0687)

216. Truck transportation (0.877)

217. Turned product and screw, nut, and bolt manufacturing (0.0023)

218. Upholstered household furniture manufacturing (0.1239)

219. Urethane and other foam product (except polystyrene) manufacturing (0.0066)

220. Vegetable and melon farming (0.1682)

221. Vending, commercial laundry, and other commercial and service industry machinery manufacturing (0.0001)

222. Veterinary services (0.2073)

223. Warehousing and storage (0.0017)

224. Waste management and remediation services (0.1586)

225. Watch, clock, and other measuring and controlling device manufacturing (0.0481)

226. Water transportation (0.1542)

227. Water, sewage and other systems (0.3104)

228. Wet corn milling (0.005)

229. Wineries (0.1439)

230. Wired telecommunications carriers (1.6334)

231. Wireless telecommunications carriers (except satellite) (0.8351)

C.2 Summary level (58 sectors)

1. Accommodation (0.9669)

2. Administrative and support services (0.452)

3. Air transportation (1.1005)

4. Ambulatory health care services (6.8389)
5. Amusements, gambling, and recreation industries (1.3236)
6. Apparel and leather and allied products (2.2705)
7. Broadcasting and telecommunications (2.4443)
8. Chemical products (1.6848)
9. Computer and electronic products (0.6861)
10. Data processing, internet publishing, and other information services (0.0563)
11. Educational services (2.2852)
12. Electrical equipment, appliances, and components (0.385)
13. Fabricated metal products (0.129)
14. Farms (0.646)
15. Federal government enterprises (0.1524)
16. Federal Reserve banks, credit intermediation, and related activities (2.1663)
17. Food and beverage and tobacco products (5.5889)
18. Food services and drinking places (5.1819)
19. Forestry, fishing, and related activities (0.0837)
20. Funds, trusts, and other financial vehicles (1.1974)
21. Furniture and related products (0.4727)
22. Hospitals (6.0657)
23. Housing (15.077)
24. Insurance carriers and related activities (3.0467)
25. Legal services (0.9665)
26. Machinery (0.1077)
27. Mining, except oil and gas (0.0066)
28. Miscellaneous manufacturing (1.002)
29. Miscellaneous professional, scientific, and technical services (0.4502)
30. Motion picture and sound recording industries (0.3772)
31. Motor vehicles, bodies and trailers, and parts (2.3893)
32. Nonmetallic mineral products (0.08)
33. Nursing and residential care facilities (1.6652)
34. Other real estate (0.0248)
35. Other retail (6.2204)

36. Other services, except government (5.3051)
37. Other transportation and support activities (0.0646)
38. Other transportation equipment (0.1696)
39. Paper products (0.2165)
40. Performing arts, spectator sports, museums, and related activities (0.4227)
41. Petroleum and coal products (1.112)
42. Plastics and rubber products (0.2733)
43. Primary metals (0.0121)
44. Printing and related support activities (0.0543)
45. Publishing industries, except internet (includes software) (0.9108)
46. Rail transportation (0.0626)
47. Rental and leasing services and lessors of intangible assets (1.1382)
48. Securities, commodity contracts, and investments (1.3039)
49. Social assistance (1.0904)
50. State and local government enterprises (0.5991)
51. Textile mills and textile product mills (0.2873)
52. Transit and ground passenger transportation (0.2739)
53. Truck transportation (0.7678)
54. Utilities (2.6471)
55. Warehousing and storage (0.0047)
56. Waste management and remediation services (0.157)
57. Water transportation (0.0982)
58. Wood products (0.0278)

Appendix D Monetary policy shocks

Figure 19: Monetary policy shocks series (1987:1-2007:12)

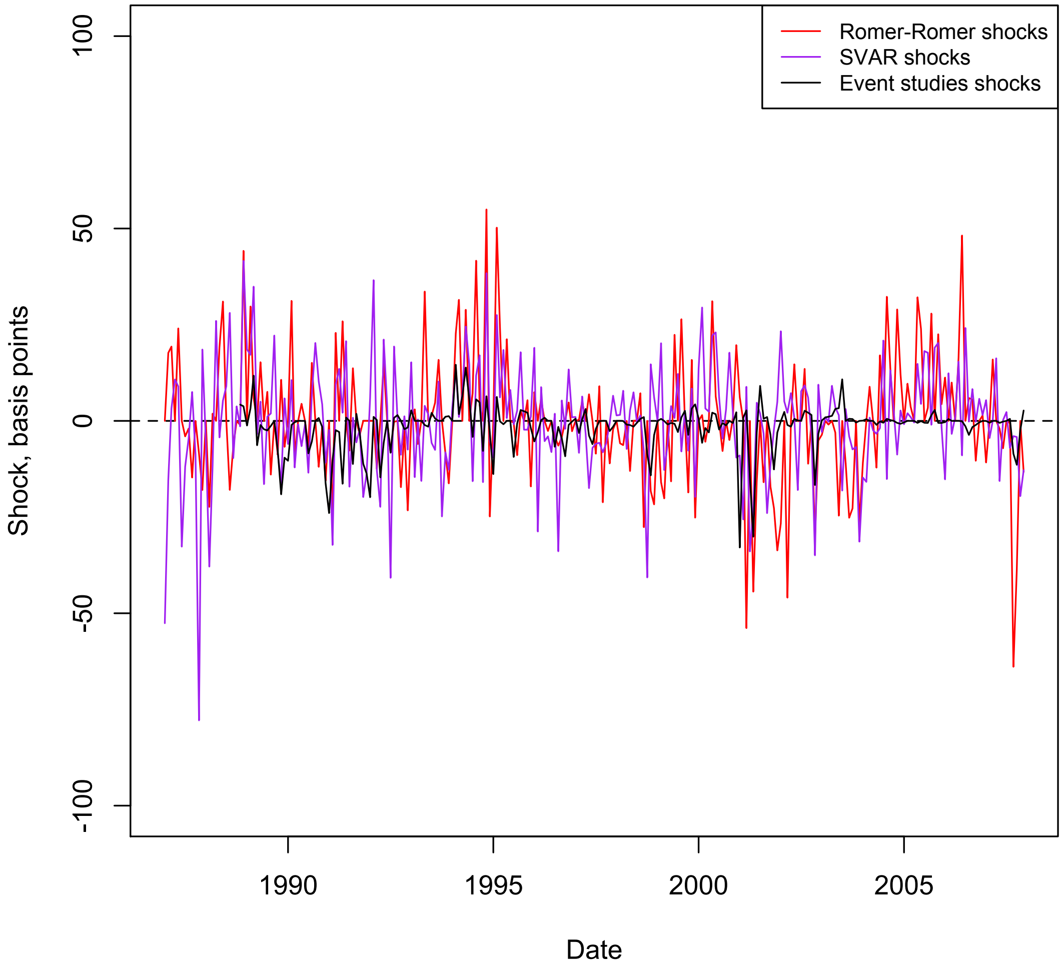


Table 1: Correlation matrix of shocks

	RR	SVAR	ES
RR	1	0.27	0.25
SVAR	0.27	1	0.35
ES	0.25	0.35	1

Table 2: Summary statistics of shocks

	RR	SVAR	ES
Mean (bp)	0.14	-0.27	-1.58
St. Dev. (bp)	15.8	15.1	5.80

Appendix E Non-smoothed impulse responses

Figure 20: Non-smooth impulse response decomposition (Detail level, 231 sectors) – Romer-Romer shocks

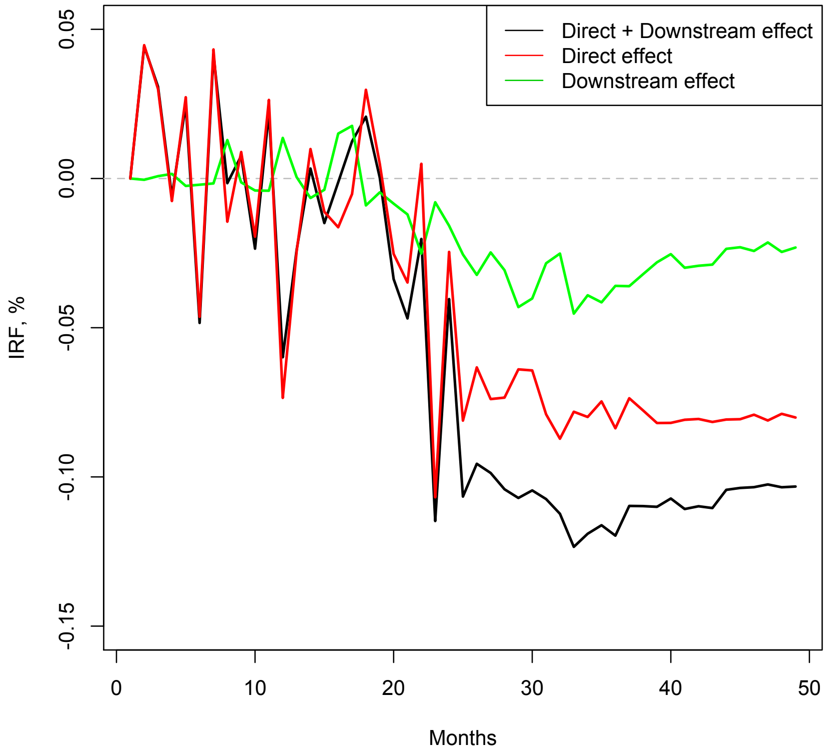


Figure 21: Non-smooth impulse response decomposition (Summary level, 58 sectors) – Romer-Romer shocks

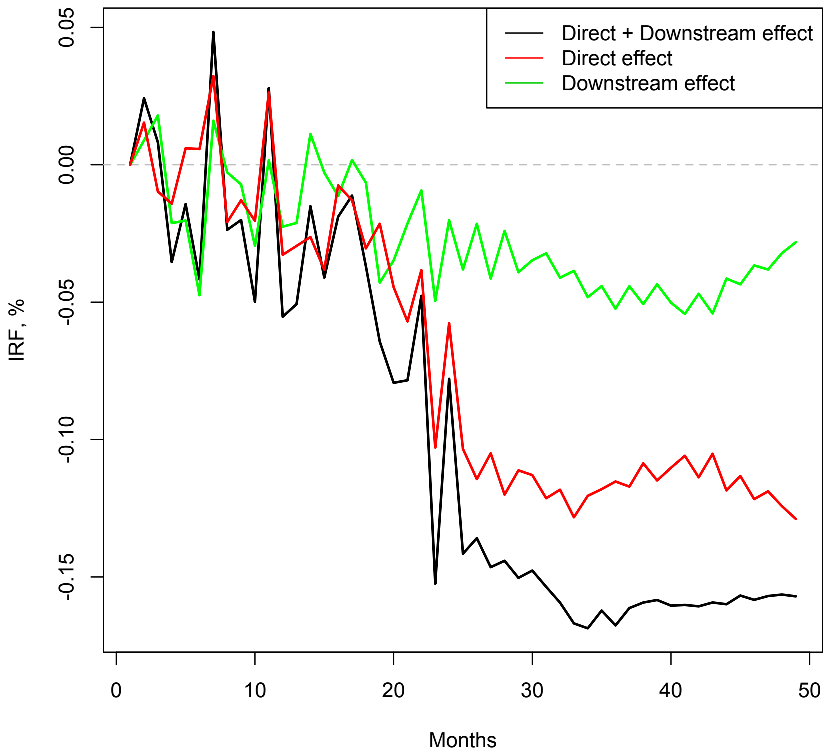


Figure 22: Non-smooth impulse response decomposition (Detail level, 231 sectors) – SVAR shocks

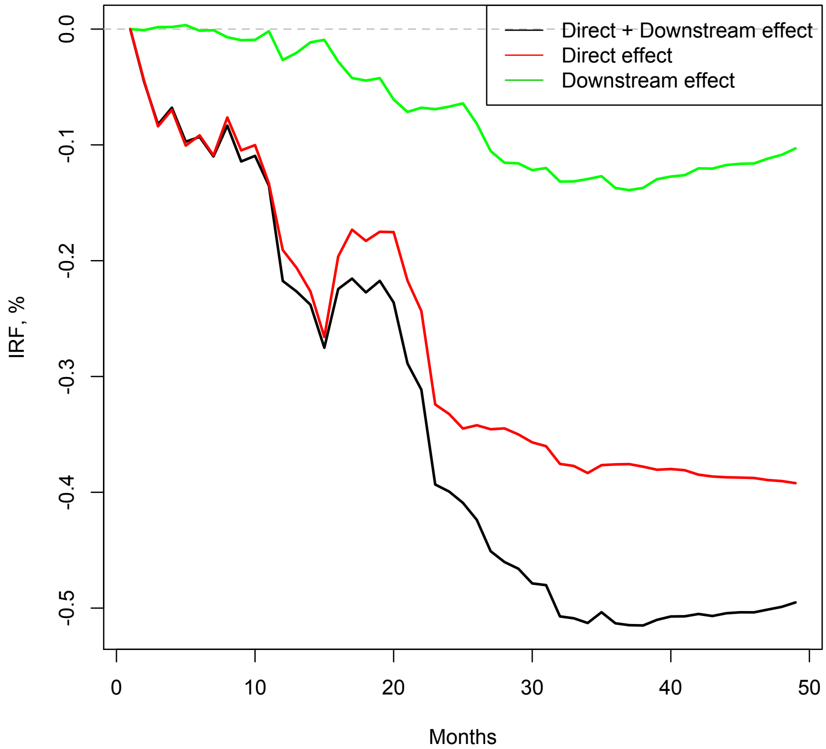


Figure 23: Non-smooth impulse response decomposition (Detail level, 231 sectors) – Event studies shocks