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# Monetary policy and production networks: an empirical investigation<sup>\*</sup>

### Mishel Ghassibe

Department of Economics, University of Oxford and National Bank of Ukraine, United Kingdom

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#### ABSTRACT

This paper offers novel econometric evidence on the contribution of production networks to the effect of monetary shocks on real macroeconomic variables. In particular, we construct a highly disaggregated monthly dataset on US final sectoral consumption to estimate that at least 30% of the effect of monetary shocks on aggregate consumption comes from amplification through input-output linkages, which facilitate downstream propagation of price rigidity. At the sectoral level, we find that the network effect rises in the frequency of price non-adjustment and intermediates intensity. Moreover, the network effect is highly concentrated: sectors that jointly account for 17% of our sample aggregate consumption account for 98% of the amplification. In order to develop our econometric specification, we obtain novel analytical sector-level solutions to a forward-looking New Keynesian model with asymmetric input-output linkages.

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#### 1. Introduction

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. Most notably, Acemoglu et al. (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 business cycle fluctuations. Such role for input-output linkages in creating aggregate fluctuations has since found support in the empirical literature (Acemoglu et al., 2016; Foerster et al., 2011).





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E-mail address: mishel.ghassibe@economics.ox.ac.uk

On the side of aggregate nominal shocks, production networks have been studied as a mechanism that enables New Keynesian models to simultaneously match microeconomic evidence on frequency of price adjustment and macroeconomic evidence on strength of monetary transmission to real variables.<sup>1</sup> 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, the latter makes firms inherit price stickiness from their suppliers, thus creating extra short-run money non-neutrality. The above theoretical mechanism has since been studied in fully specified multi-sector quantitative models (Carvalho et al., 2021; Nakamura and Steinsson, 2010; Pasten et al., 2020). However, econometric 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 gap in the literature.

Our paper is the first study to offer econometric evidence on the role of production networks in creating short-run monetary non-neutrality of real macroeconomic variables. In particular, our empirical contribution is in establishing the following results. First, at least 30 per cent of the effect of monetary policy shocks on US real aggregate final consumption is due to production networks, which facilitate downstream propagation of price rigidity. This result is robust to varying the degree of sectoral disaggregation and the type of monetary shocks used. Second, we document substantial heterogeneity in network amplification across sectors and further examine its dimensions. Our cross-sectional analysis suggests that the network effect is, *ceteris paribus*, larger for sectors that adjust prices less frequently and for those that rely more on intermediate inputs; moreover, we rationalize such results through the lens of our theoretical model. Third, we show that the aggregate network contribution is highly concentrated in the sense of being driven by a relatively small number of sectors; quantitatively, sectors that jointly account for 17 per cent of our sample aggregate consumption account for 98 per cent of the amplification by production networks.<sup>2</sup>

Our econometric specification is derived from a multi-sector New Keynesian model with asymmetric input-output linkages, and we make two theoretical contributions that allow us to form a tractable econometric strategy. First, we formally show that the response of sectoral final consumption to a monetary shock can be decomposed into the *direct effect*, driven by that sector's own frequency of price non-adjustment, and the *downstream effect*, driven by persistence in price setting inherited from supplier sectors and the intensity with which intermediates are used. It is the downstream effect that represents network amplification of monetary shocks. Second, we consider a finite-time version of our model, where we use backward induction in order to find novel analytical solutions for sectoral final consumptions. Those solutions directly imply a simple econometric strategy based on linear regressions that allows to consistently estimate a lower bound for the downstream effect. Our analytical solutions introduce a novel concept of the *Forward-looking Leontief Inverse*, which can be used to find analytical solutions to other problems featuring production networks and nominal rigidities in a forward-looking setting. Previous studies, such as Pasten et al. (2020), instead rely on myopic firms or other deviations from forward-looking behavior in order to obtain sector-level closed-form results.

Estimating our econometric specification requires sectoral final consumption time series whose classification matches that used in input-output accounts. Such time series are not readily available for the US, and our paper makes a further contribution by constructing a novel monthly dataset for sectoral final consumptions for up to 161 sectors of the US economy, whose classification matches that in the US Bureau of Economic Analysis (BEA) input-output accounts. In particular, we take monthly product-level consumption and consumer price time series contained in NIPA tables and use PCE Bridge Tables to match NIPA product definitions to sectoral classifications of the US BEA. In this way, our sectoral final consumption series are consistent in their classification with the sectoral classification used by BEA for their input-output-tables, and can be used together in our econometric analysis. To the best of our knowledge, we are the first ones to construct a monthly dataset for sectoral final consumption that uses classification consistent with BEA input-output accounts.

**Contribution to the literature.** Our results should be viewed in the context of at least two strands of existing literature.<sup>3</sup> First, we contribute to the empirical literature that studies the extent to which production networks amplify the effects of economic shocks. On the side of sector-specific shocks, Acemoglu et al. (2016) 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 (2017) 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. Our work makes a contribution in at least two substantial ways. First, we focus on the effect of monetary shocks on real macroeconomic variables, most specifically final consumption, whereas Ozdagli and Weber (2017) study stock market responses. Second, we empirically assess a completely different theoretical mechanism: our specification estimates contribution of production networks that comes from complementarities in price setting and downstream propagation of price rigidity, whereas Ozdagli and Weber

<sup>&</sup>lt;sup>1</sup> As discussed in Mackowiak and Smets (2008), in order to match VAR-based estimates of the effect of monetary shocks on real variables, a New Keynesian model with no additional real rigidities needs to be calibrated with a frequency of price adjustment much lower than that observed in microeconomic studies.

<sup>&</sup>lt;sup>2</sup> Specifically, those broad sectoral groups are "Transportation and warehousing", "Retail trade", "Information", "Agriculture, forestry, fishing and hunting" and "Professional and business services".

<sup>&</sup>lt;sup>3</sup> See Carvalho and Tahbaz-Salehi (2019) for a comprehensive review of the literature on production networks in macroeconomics.

(2017) build their specification in a flexible-price framework and consider upstream propagation of demand created by monetary shocks and the effect on stock market returns.

Secondly, our results add to the quantitative theory literature on complementarities in price setting and monetary policy under 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 et al. (2020) develop a multi-sector model with sector-specific probabilities of price adjustment that they calibrate to 341 sectors of the US economy and confirm large amplifications of monetary policy shocks coming from strategic complementarities in price setting. As for optimal monetary policy under production networks, it is studied in La'O and Tahbaz-Salehi (2019).

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, Smets et al. (2019) use Bayesian techniques to estimate a 35-sector model on US data, and subsequently study the role of production networks for inflation dynamics; Carvalho et al. (2021) estimate sector-specific probabilities of price adjustment for 27 major sectors of the US economy, and show that the estimated model successfully replicates sectoral price responses to both idiosyncratic and aggregate shocks from Boivin et al. (2009). In addition, Bouakez et al. (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).

The rest of the paper is structured as follows. In Section 2 we build a theoretical framework and derive analytical solutions for sectoral consumptions that informs our econometric specification. Section 3 outlines the construction of our dataset. Our econometric strategy is detailed in Section 4. Sections 5 and 6 discuss the main empirical results of this paper, whose robustness is then tested in Section 7. Section 8 concludes and outlines our strategy for future work.

#### 2. Model

In this section, we formalize our ideas in the context of a multi-sector New Keynesian model with production networks. Our theoretical contribution is twofold. First, we formally show that the response of sectoral consumption to a monetary shock can be decomposed into the *direct effect*, driven by sector's own price stickiness, and the *downstream effect*, driven by stickiness of suppliers and the intensity with which intermediates are used. Second, we find novel analytical solutions for sectoral final consumptions by considering a version of our model in finite time; all proofs are given in Appendix B.

#### 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*, that each belongs to one sector; let  $\Phi_k$  denote the set of all firms in sector *k*. The production function of firm *j* that operates in sector *k* is given by:

$$Y_{kt}(j) = N_{kt}(j)^{1-\delta_k} Z_{kt}(j)^{\delta_k} - \Xi_k(j), \tag{1}$$

where  $Y_{kt}(j)$ ,  $N_{kt}(j)$  and  $Z_{kt}(j)$  are, respectively, total output, labor input and intermediate inputs used,  $\delta_k$  is intermediates intensity that is allowed to be sector-specific,  $\Xi_k(j)$  is a fixed cost which is set to equalize steady-state profits to zero and rule out entry and exit.

Total intermediate inputs used is an aggregate of intermediate goods purchased from all the different sectors in the economy, so that  $Z_{kt}(j) \equiv \prod_{r=1}^{K} \omega_{kr}^{-\omega_{kr}} Z_{krt}^{\omega_{kr}}(j)$ , where  $Z_{krt}(j)$  is the intermediate inputs purchased by firm j in sector k from all firms in sector r;  $\omega_{kr}$  is the relative intensity with which firms in sector k use goods produced in sector r as inputs, so that  $\sum_{r=1}^{K} \omega_{kr} = 1$   $\forall k$ . In turn,  $Z_{krt}(j)$  is also an aggregator for all the inputs purchased from the different firms that belong to sector r, namely  $Z_{krt}(j) \equiv \left(\int_{\Phi_r} Z_{krt}(j, j')^{\frac{\theta-1}{\theta}} dj'\right)^{\frac{\theta}{\theta-1}}$ , where  $Z_{krt}(j, j')$  denotes total inputs purchased by firm j in sector k from firm j' in sector r.

Given the sectoral nominal wage  $W_{kt}$  and the input price index  $P_t^k$ ,  $P_t^k \equiv \prod_{r=1}^{K} P_{rt}^{\omega_{kr}}$ , firms choose  $N_{kt}(j)$  and  $Z_{kt}(j)$  in order to minimize their total inputs cost subject to the production function in (1). The latter delivers the the optimal labor/intermediate inputs mix condition  $\frac{Z_{kt}(j)}{N_{kt}(j)} = \frac{\delta_k}{1-\delta_k} \frac{W_{kt}}{P_t^k}$  and for the nominal marginal cost, common to all firms within a given sector:

$$MC_{kt}(j) = MC_{kt} = \frac{\delta_k^{-\delta_k}}{(1-\delta_k)^{1-\delta_k}} W_{kt}^{1-\delta_k} \left[ \prod_{r=1}^K P_{rt}^{\omega_{kr}} \right]^{\delta_k}.$$
(2)

One can see that the marginal cost for any firm is effectively a weighted average of its labor input cost, given by the wage, and its sector-specific inputs price index, whose relative importance increases in the share of intermediate inputs  $\delta_k$ . It can also be seen how  $\delta_k > 0$  makes the marginal cost of any firm sensitive to prices set by its suppliers. This is

the mechanism through which production networks create complementarities in price setting, which in turn amplifies the degree of monetary non-neutrality in our economy.

Price stickiness in our economy is modeled as in Calvo (1983), although the probability of price adjustment is allowed to vary across sectors. More precisely, in 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 maximize expected future discounted nominal profits:

$$\max_{P_{kt}(j)} \mathbb{E}_{t} \sum_{s=0}^{\infty} \alpha_{k}^{s} F_{t,t+s}(P_{kt}(j)Y_{k,t+s}(j) - W_{k,t+s}N_{k,t+s}(j) - P_{t+s}^{k}Z_{k,t+s}(j)),$$
(3)

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 and the marginal cost equation from (2), the first order condition for the optimal reset price for any firm in sector k,  $P_{kt}^*$  is given by  $P_{kt}^* = \frac{\theta}{\theta-1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \alpha_k^s F_{t,t+s} P_{k,t+s}^{\theta} N_{k,t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} \alpha_k^s F_{t,t+s} P_{k,t+s}^{\theta} Y_{k,t+s}}$ . Given that the optimal reset price is identical for all firms within a sector, sectoral price index can be obtained by simple aggregation:  $P_{kt} = \left[\alpha_k P_{k,t-1}^{1-\theta} + (1-\alpha_k)(P_{kt}^*)^{1-\theta}\right]^{\frac{1}{1-\theta}}$ .

#### 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 household makes choices to maximize the lifetime utility:

$$\max_{\{C_{t+s},\{N_{k,t+s}\}_{k=1}^{K},B_{t+s+1}\}_{s=0}^{\infty}} \mathbb{E}_{t} \sum_{s=0}^{\infty} \beta^{s} \left[ \ln(C_{t+s}) - \sum_{k=1}^{K} g_{k} N_{k,t+s} \right]$$
(4)

subject to

$$P_t^c C_t + \mathbb{E}_t [F_{t,t+1} B_{t+1}] \le B_t + \sum_{k=1}^K W_{kt} N_{kt} + \sum_{k=1}^K \Pi_{kt}, \quad \forall t$$
(5)

where  $C_t$  and  $P_t^c$  are the composite consumption good and the consumption price index (defined below) respectively,  $N_{kt}$  is sectoral labor 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  $\Pi_{kt}$  denotes aggregate nominal profits of firms in sector k;  $\beta$  is the discount factor for future utility and  $g_k$  is a parameter capturing the relative disutility of sector-specific labor supply.

The composite consumption index  $C_t$  is an aggregator for the final consumption of goods produced in the different sectors of our economy, so that  $C_t \equiv \prod_{k=1}^{K} \omega_{ck}^{-\omega_{ck}} C_{kt}^{\omega_{ck}}$ , where  $\omega_{ck}$  is the relative weight consumers put on goods produced in sector k,  $\sum_{k=1}^{K} \omega_{ck} = 1$ ;  $C_{kt}$  is in turn an aggregator for the final consumption of goods produced by firms that belong to sector k:  $C_{t\pi} \equiv \left(\int_{c_{\pi}} C_{t\pi}(i) \frac{\theta^{-1}}{\theta} di\right)^{\frac{\theta}{\theta-1}}$ .

 $C_{kt} \equiv \left( \int_{\Phi_r} C_{kt}(j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}}.$ The households' maximization problem delivers standard first-order conditions, namely an equation for the stochastic discount factor  $F_{t,t+s} = \beta^s \left(\frac{C_{t+s}}{C_t}\right)^{-1} \frac{P_t^c}{P_{t+s}^c}$ , and equations for consumption-sectoral labor supply choice  $C_t^{-1} = g_k \frac{P_t^c}{W_{kt}}$ ,  $\forall k$ , where the consumption price index is given by  $P_t^c = \prod_{k=1}^K P_{kt}^{\omega_{ck}}.$ 

#### 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  $M_t \equiv P_t^c C_t$ , follows an exogenous process:

$$\ln M_t = \ln M_{t-1} + r_t, (6)$$

where  $r_t = \rho_r r_{t-1} + \varepsilon_t^r$  defines an AR(1) process for monetary policy shocks, and innovations  $\{\varepsilon_t^r\}_t$  constitute a zero-mean white noise process with variance  $\sigma_r^2$ . The above can be rationalized by imposing a cash-in-advance constraint on aggregate final consumption, and assuming a constant velocity of money. As discussed in Nakamura and Steinsson (2013), under such assumptions the process in (6) is equivalent to a rule for money supply.<sup>4</sup>

For the remainder of the main text we focus on the simplified case of non-persistent monetary shocks ( $\rho_r = 0$ ); however, in Appendix B we provide formal analytical results for the case of persistent shocks ( $|\rho_r| \in (0, 1)$ ).

<sup>&</sup>lt;sup>4</sup> An alternative would be to close our model with a Taylor rule for the nominal interest rate, which comes at the cost of analytical tractability. In Section 7 we report numerical exercises with a Taylor rule.

#### 2.4. Market clearing

In addition to the optimality conditions, budget constraints and the policy rule above, equilibrium in our economy is also characterized by market-clearing conditions in the asset market:  $B_t = 0$ ; the labor markets:  $N_{kt} = \int_{\Phi_k} N_{kt}(j)dj$ ,  $\forall k$ ; and the goods markets:  $Y_{kt}(j) = C_{kt}(j) + \sum_{r=1}^{K} \int_{\Phi_r} Z_{rkt}(j', j)dj'$ ,  $\forall k, \forall j \in \Phi_k$ .

#### 2.5. Log-linearized equilibrium

We log-linearize the equilibrium conditions from the previous subsections around a symmetric zero-inflation steadystate. In Appendix A we fully characterize both the steady state and the log-linearized system; here we instead focus on the resulting sectoral pricing equations (lower case letters denote log-deviations from the steady state):

$$p_{kt} = \alpha_k p_{k,t-1} + (1 - \delta_k)(1 - \alpha_k)m_t + \delta_k(1 - \alpha_k)(1 - \beta \alpha_k) \sum_{s=0}^{\infty} (\beta \alpha_k)^s \sum_{r=1}^K \omega_{kr} \mathbb{E}_t p_{r,t+s},$$
(7)

for k = 1, 2, ..., K. One can clearly see that every sectoral price is now positively related to every other sectoral price in the economy, both current and those expected in future periods, weighted by the input-output entry between the respective sectors and increasing in the share of intermediate inputs  $\delta_k$ . As a result, persistence in price adjustment can travel from supplier sectors to customer sectors, leading to slower adjustment of sectoral prices.

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. The following proposition formalizes the above statement for the sectoral consumption:

**Proposition 1.** The response of final consumption in sector  $k c_{kt}$  to a monetary shock  $r_t$  is given by:

$$c_{kt} = \overbrace{\alpha_k c_{k,t-1} + \alpha_k r_t}^{\text{Direct effect}} + \underbrace{\delta_k (1 - \alpha_k) (1 - \beta \alpha_k) \sum_{s=0}^{\infty} (\beta \alpha_k)^s \sum_{r=1}^{K} \omega_{kr} \mathbb{E}_t c_{r,t+s}}_{\text{Downstream effect}},$$
(8)

for k = 1, 2, ..., K. It consists of the the direct effect, unaffected by the intermediate inputs share  $\delta_k$ , and the downstream effect, which fully vanishes under  $\delta_k = 0$  and increases in  $\delta_k$ , representing amplification through input-output linkages.

Proposition 1 establishes that the effect of a monetary shock  $r_t$  on sectoral final consumption can be decomposed into the *direct effect*, caused by that sector's own price stickiness and hence independent of  $\delta_k$ , and the *downstream effect*, caused by price stickiness inherited from that sector's suppliers and hence increasing in  $\delta_k$  and disappearing under  $\delta_k = 0$ . It is therefore the downstream effect that represents the amplification of the effect of monetary shocks through input-output linkages. Intuitively, the direct effect strictly increases in sector's own probability of price non-adjustment  $\alpha_k$ . As for the downstream effect, two opposing channels of own price stickiness are at work. On the one hand, higher  $\alpha_k$  reduces sector *k*'s price sensitivity to its current and expected future marginal costs, making it harder to inherit stickiness from suppliers, thus dampening the downstream effect; on the other hand, higher  $\alpha_k$  makes sector *k*'s optimal price more sensitive to expected future marginal costs (as any price set is more likely to persist in the future), thus amplifying the downstream effect.

A natural next step is to find a solution for sectoral consumption that can then be used to empirically disentangle the direct and downstream effects. Due to a number of asymmetries, however, such as heterogeneous input-output weights  $\{\omega_{kr}\}_{k,r}$  and Calvo parameters  $\{\alpha_k\}_k$  one cannot easily find a sector-level analytical solution to the above problem. However, in the next subsection we show how a slight modification to our model, featuring finite time, enables us to find analytical solution for sectoral consumption.<sup>5</sup>

#### 2.6. Analytical solution in finite time

In this subsection we propose a slight modification to our original model that allows to find analytical solutions for sectoral price indices and final consumptions. In particular, we assume that the economy exists for a finite deterministic number of time periods T > 1, and firms face a Calvo lottery between periods 1 and T - 1, whereas in the final period T all firms get to adjust their prices. The assumptions are summarized below:

**Assumption 1.** The economy exists for a finite deterministic number of periods T > 1.

**Assumption 2.** In periods t = 1, 2, ..., T - 1 every firm faces a Calvo lottery with a sector-specific probability of price nonadjustment given by  $\alpha_k$ ; in period T all firms get to set their prices optimally.

<sup>&</sup>lt;sup>5</sup> In Appendix C we numerically solve a simple calibrated three-sector (K = 3) example in the infinite-horizon case, allowing us to gain further intuition behind monetary transmission and the role of production networks.

Note that the above two assumptions have no implications for the households' problem. In particular, the intratemporal consumption-labor supply choice equations remain unchanged for all t = 1, 2, ..., T, and the equation for the stochastic discount factor remains valid for any  $1 \le t, t + s \le T - 1$ .

Slight modifications happen on the firms' side, however. In period t = T, the representative firm in sector k solves a static problem of choosing price  $P_{kT}(j)$  to maximize contemporaneous profits  $\prod_{kT}(j) = (P_{kT}(j)Y_{kT}(j) - W_{kT}N_{kT}(j) - P_T^kZ_{kT}(j))$ , subject to the production function in (1); given no restrictions on price setting, every firm sets the same optimal price at a constant mark-up to the marginal cost, so that  $P_{kT} = P_{kT}^* = \frac{\theta}{\theta-1}MC_{kT}$ ,  $\forall k$ , or  $p_{kT} = p_{kT}^* = m_{c}T = m_T$  in log-linear terms. Consequently, money is neutral at t = T, and  $c_{kT} = c_T = 0$ ,  $\forall k$ .

In period  $1 \le t \le T - 1$ , the representative firm in sector k chooses its price to maximize expected future discounted nominal profits between periods t and T - 1, as in T it will get to re-set prices with certainty. The latter delivers a familiar expression for the optimal price, shared by all firms in sector k:  $P_{kt}^* = \frac{\theta}{\theta - 1} \frac{\mathbb{E}_t \sum_{s=0}^{T-t-1} \alpha_k^s \mathbb{I}_{t,t+s} \mathcal{P}_{k,t+s}^{\theta} \mathcal{N}_{k,t+s}}{\mathbb{E}_t \sum_{s=0}^{T-t-1} \alpha_k^s \mathbb{I}_{t,t+s} \mathcal{P}_{k,t+s}^{\theta} \mathcal{N}_{k,t+s}}$ ,  $1 \le t \le T - 1$ ,  $\forall k$ , or, when written in log-linear terms:  $p_{kt}^* = \frac{1 - \beta \alpha_k}{1 - (\beta \alpha_k)^{T-t}} \sum_{s=0}^{T-t-1} (\beta \alpha_k)^s \mathbb{E}_t mc_{k,t+s}$ ,  $1 \le t \le T - 1$ ,  $\forall k$ . In every period  $1 \le t \le T - 1$ ,  $\forall k$ .

or, when written in log-inhear terms:  $p_{kt} = \frac{1}{1 - (\beta \alpha_k)^{T-t}} \sum_{s=0} (p \alpha_k)^s \mathbb{E}_t m c_{k,t+s}$ ,  $1 \le t \le T-1$ ,  $\forall k$ . In every period  $1 \le t \le T-1$  every firm is still subject to the Calvo lottery with a sector-specific probability of price non-adjustment  $\alpha_k$ . Given the optimal sectoral price  $p_{kt}^*$ , the sectoral price index is then given by  $p_{kt} = \alpha_k p_{k,t-1} + (1 - \alpha_k) p_{kt}^*$ ,  $1 \le t \le T-1$ ,  $\forall k$ .

One can now obtain the finite-time equivalent of the sectoral price Eq. (7), highlighting complementarities in price setting; for compactness, we let  $p_t \equiv [p_{1t}, p_{2t}, \dots, p_{Kt}]'$ ,  $m_t \equiv [m_t, m_t, \dots, m_t]'$ ,  $A \equiv diag[\alpha_1, \alpha_2, \dots, \alpha_K]'$ ,  $\Delta \equiv diag[\delta_1, \delta_2, \dots, \delta_K]'$ ,  $G_{T-t} \equiv (I - \beta A)(I - (\beta A)^{T-t})^{-1}$  and write it in matrix form as:

$$p_{t} = A_{p_{t-1}} + (I - \Delta)(I - A)m_{t} + \Delta(I - A)G_{T-t} \sum_{s=0}^{T-t-1} (\beta A)^{s} \Omega \mathbb{E}_{t \, p_{t+s}}$$
(9)

for  $1 \le t \le T - 1$ . Further, recall that  $c_{kt} = p_t^c + c_t - p_{kt} = m_t - p_{kt}$ , and letting  $c_t \equiv [c_{1t}, c_{2t}, \dots, c_{Kt}]'$ ,  $r_t \equiv [r_t, r_t, \dots, r_t]'$  we can write the finite-time equation for sectoral consumption as:

$$\mathfrak{c}_{t} = A\mathfrak{c}_{t-1} + A\mathfrak{r}_{t} + \Delta(I-A)G_{T-t}\sum_{s=0}^{T-t-1} (\beta A)^{s}\Omega\mathbb{E}_{t}\mathfrak{c}_{t+s}$$

$$\tag{10}$$

for  $1 \le t \le T - 1$ ; which is just the finite-time version of the direct-downstream effect decomposition from Proposition 1.

It should now be clear how Eqs. (9) and (10) allow us to use backward induction to find analytical solutions for sectoral prices and consumptions respectively. Here we focus on the case of consumptions, although the same procedure can be applied to prices. According to (10), at t = T - 1 sectoral consumptions vector is given by:

$$c_{T-1} = Ac_{T-2} + Ac_{T-1} + \Delta(I-A)G_1\Omega c_{T-1},$$
(11)

and it follows that  $\mathbb{C}_{T-1} = [I - \Delta(I - A)G_1\Omega]^{-1}A\mathbb{C}_{T-2} + [I - \Delta(I - A)G_1\Omega]^{-1}A\mathbb{C}_{T-1}$ . Similarly, at t = T - 2:

$$T_{T-2} = A c_{T-3} + A r_{T-2} + \Delta (I - A) G_2 [\Omega c_{T-2} + (\beta A) \Omega \mathbb{E}_{T-2} c_{T-1}],$$
(12)

but note that we have already solved for  $c_{T-1}$  above, so  $\mathbb{E}_{T-2}c_{T-1}$  can be easily found, allowing to find a solution for  $c_{T-2}$ . One can then repeat this procedure all the way back to  $c_1$ , and find analytical solutions along the way. All in all, one can use the strong induction principle to show that analytical solution for generic  $c_t$ ,  $1 \le t \le T - 1$ , can be written down using the notion of the *Forward-looking Leontief Inverse*, as formally introduced in the following proposition.

**Proposition 2.** The response of final sectoral consumption  $c_{kt}$  to a monetary policy shock  $r_t$  is

$$c_{kt} = \sum_{r=1}^{K} l_{kr,T-t} \alpha_r c_{r,t-1} + \tilde{\alpha}_{k,T-t} r_t, \qquad 1 \le t \le T - 1$$
(13)

where  $\tilde{\alpha}_{k,T-t}$  is

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$$\tilde{\alpha}_{k,T-t} \equiv \alpha_k + (l_{kk,T-t} - 1)\alpha_k + \sum_{r \neq k} l_{kr,T-t}\alpha_r,$$
(14)

and  $\{l_{ki,T-t}\}_{ki}$  are entries of the Forward-looking Leontief Inverse:

$$L_{T-t} = \underbrace{\left[I - \Delta(I-A)G_{T-t}\sum_{s=0}^{T-t-1} (\beta A)^{s} \Omega\left\{\Pi_{j=T-t-s}^{T-t-1} L_{j}A\right\}\right]^{-1}}_{\text{Forward-looking Leontief Inverse}},$$
(15)

where  $A \equiv diag[\alpha_1, \alpha_2, \dots, \alpha_K]'$ ,  $\Delta \equiv diag[\delta_1, \delta_2, \dots, \delta_K]'$ ,  $G_{T-t} \equiv (I - \beta A)(I - (\beta A)^{T-t})^{-1}$  and  $\Omega$  is the input-output matrix.

Note that for  $\delta_k = 0$ ,  $\forall k$ , the Forward-looking Leontief Inverse collapses to the identity matrix, so that  $L_{T-t} = I$ ,  $\forall 1 \le t \le T-1$ , and  $c_{kt} = \alpha_k c_{k,t-1} + \alpha_k r_t$ , which is exactly the *direct effect* defined earlier. However, for  $\delta_k > 0$  the coefficients on lagged consumption and monetary policy shocks are instead given by a weighted sum of a sector's own Calvo parameter and the Calvo parameters of its suppliers.

#### 2.7. Analytical impulse response functions

Having obtained analytical solutions for sectoral consumptions, we can now solve for the horizon-specific impulse responses of sectoral consumptions to a monetary shock:

**Corollary 1.** [Full IRF] Suppose the economy is in steady state until the beginning of period t; the impulse response of final sectoral consumption  $c_{kt}$ , k = 1, 2, ..., K at horizon  $H \ge 0$ , following a one-time monetary policy shock  $r_t$  is given by:

$$c_{k,t+H} = \tilde{\tilde{\alpha}}_{k,T-t}^{H} r_t, \qquad 1 \le t, t+H \le T-1$$
(16)

where  $\tilde{\alpha}_{k,T-t}^{H} \equiv \sum_{r=1}^{K} \left[ \prod_{j=T-t-H}^{T-t} L_{j} A \right]_{kr}$ ,  $L_{j}$  is period-j Forward-looking Leontief Inverse,  $A \equiv diag[\alpha_{1}, \alpha_{2}, \dots, \alpha_{K}]'$ . Therefore,  $\frac{dc_{k,t+H}}{dr_t} = \tilde{\tilde{\alpha}}^H_{\nu T_- t}$ .

In other words, in a linear projection of final sectoral consumption at t + H on a monetary policy shock at t, the coefficient on the latter gives the horizon-*H* impulse response.

Moreover, one can derive an alternative representation of the horizon-specific impulse response of sectoral final consumption, which allows to separate out an upper bound of the *direct effect*, as defined in Proposition 1. The next corollary formalizes this statement:

**Corollary 2.** [Upper Bound of Direct IRF] Suppose the economy is in steady state until the beginning of period t; the impulse response of final sectoral consumption  $c_{kt}$ , k = 1, 2, ..., K at horizon  $H \ge 1$ , following a one-time monetary policy shock  $r_t$  can be written as follows:

$$c_{k,t+H} = \left\{ \alpha_k^{H+1} + \delta_k q_{T-t-H,H}^k \right\} r_t + \sum_{\tau=1}^H \delta_k s_{T-t-H+\tau}^k \sum_{r=1}^K \omega_{kr} c_{r,t+H-\tau}, \qquad 1 \le t, t+H \le T-1$$
(17)

v

δ

$$\begin{aligned} & \text{where} \qquad q_{T-t-H,H}^{k} \equiv \sum_{j=1}^{K} \left[ \mathbb{Q}_{T-t-H,H} \right]_{kj} \geq 0, \quad s_{T-t-H+\tau}^{k} \equiv \alpha_{k}^{\tau} (1-\alpha_{k}) g_{T-t-H+\tau}, \\ & g_{T-t-H+\tau} = [G_{T-t-H+\tau}]_{kk}, \\ & \mathbb{Q}_{T-t,\tau} = \left[ (I-A) G_{x} \left[ \sum_{s=1}^{x-1} (\beta A)^{s} \Omega \left\{ \prod_{j=x-s}^{x+y} L_{j} A \right\} \right] \right]. \quad \text{Hence,} \quad \frac{\partial c_{k,t+H}}{\partial r_{t}} = \alpha_{k}^{H+1} + k q_{T-t-H,H}^{k} \geq \alpha_{k}^{H+1}. \end{aligned}$$

Verbally, Corollary 2 establishes that in a linear projection of sectoral final consumption at t + H on a monetary policy shock at t and a weighted average of all other sectors' final consumptions between t and t + H - 1, the coefficient on the monetary policy shock  $(\alpha_k^{H+1} + \delta_k q_{t-t-H,H}^k)$  is an upper bound for the true horizon-*H* direct effect  $(\alpha_k^{H+1})$ . Importantly, since in Corollary 1  $\tilde{\alpha}_{k,T-t}^{H}$  gives the sectoral full effect, and in Corollary 2

 $(\alpha_k^{H+1} + \delta_k q_{T-t-H,H}^k)$  gives an *upper bound* for the sectoral direct effect, the difference between the two, given by  $\left[\tilde{\alpha}_{k,T-t}^{H} - \left(\alpha_{k}^{H+1} + \delta_{k}q_{T-t-H,H}^{k}\right)\right]$ , gives a *lower bound* for the sectoral downstream effect.<sup>6</sup> In Section 4 we use the analytical expressions in Corollaries 1 and 2 to directly inform our econometric specification.

However, before that, we outline the construction of our dataset.

#### 3. Data

This section contains an overview of the data used in our empirical analysis. More details are given in the Online Appendix.

#### 3.1. Sectoral consumption

We use the underlying detail tables of NIPA accounts published by the United States 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 maximize the number of sectors 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 is 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 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. In particular, we use the PCE Bridge Tables in order construct weights  $\{\zeta_{ki}\}_{ki}$ , which give the share of sector k from BEA IO accounts in sector i from NIPA accounts. Then, given the time series of final sectoral consumptions based on NIPA accounts, we construct time series of final consumptions consistent with BEA IO sector definitions:

$$c_{kt}^{BEA} = \sum_{i=1}^{K^{NIPA}} \zeta_{ki} c_{it}^{NIPA}, \qquad k = 1, 2, \dots, K$$
(18)

<sup>&</sup>lt;sup>6</sup> Appendix B formally extends Corollaries 1 and 2 for the case where  $|\rho_r| \in (0, 1)$ .

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 Appendix E.

At the Detail level, which is our baseline sample, we have constructed data for 161 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 minimize the number of sectors 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 83 per cent of aggregate real Personal Consumption Expenditure (PCE).

At the less disaggregated Summary level, we have only constructed data for 53 sectors, but the advantage of this level of disaggregation is the longer time series available (1976:1 until 2015:12). The consumption series constructed account for around 84 per cent of aggregate real Personal Consumption Expenditure (PCE) over the sample.<sup>7</sup>

#### 3.2. Input-output weights, consumption shares and intermediates intensities

In equilibrium, the input-output weight  $\omega_{kr}$  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. Similarly, the final consumption share  $\omega_{ck}$  is the share of households' final consumption expenditure that goes to firms in sector k. As for the intermediates intensity  $\delta_k$ , we know that in equilibrium  $\delta_k/(1 - \delta_k)$  is given by  $P_t^k Z_{kt}(j)/W_{kt} N_{kt}(j)$ . Following aggregation over all firms in a given sector, we can write  $\omega_{kr}$ ,  $\omega_{ck}$  and  $\delta_k$  as:

$$\omega_{kr} = \frac{P_{rt}Z_{krt}}{P_t^k Z_{kt}}, \quad \forall k, r \qquad \qquad \omega_{ck} = \frac{P_{kt}C_{kt}}{P_t^c C_t}, \quad \forall k \qquad \qquad \frac{\delta_k}{1 - \delta_k} = \frac{P_t^k Z_{kt}}{W_{kt} N_{kt}}, \quad \forall k, \tag{19}$$

We use data from the 2007 annual "*Make*" and "*Use*" tables, published by the US Bureau of Economic Analysis (BEA) as part of its Input-Output accounts, in order to evaluate  $\omega_{kr}$ ,  $\omega_{ck}$  and  $\delta_k$ . The exact details behind the evaluation are given in Appendix F.

#### 3.3. Sectoral Calvo paramaters

We measure sectoral Calvo parameters as one minus the sectoral frequency of price adjustment, as constructed by Pasten et al. (2020). Their measure is based on confidential firm-level pricing data from the US Bureau of Labor Statistics (BLS).<sup>8</sup>

#### 3.4. Monetary policy shocks

Our baseline measure of US monetary policy shocks comes from Romer and Romer (2004), available between 1969:1 and 1996:12, and extended by Wieland and Yang (2016) until 2007:12.

We also consider monetary policy shocks identified using different strategies.<sup>9</sup> First, we consider shocks recursively identified from a structural vector autoregression (SVAR) in Coibion (2012).<sup>10</sup> Second, we consider monetary policy shocks identified using event studies and high frequency data, from Kuttner (2001).<sup>11</sup> In Appendix H, we provide summary statistics and time series plots for all three monetary policy shocks measures.

#### 4. Econometric strategy

In this section we develop our econometric specification, based on the analytical solutions for sectoral consumption obtained in Section 2.

<sup>&</sup>lt;sup>7</sup> We report results using the less disaggregated Summary level accounts in Appendix K. Despite the lower degree of disaggregation, estimation at Summary level allows us to extend our estimation sample back to 1976:1, thus benefiting from a higher number of identified monetary shocks. When estimated sector-by-sector and aggregated, the downstream effect contribution is at least 47 per cent of the cumulative full effect, with panel fixed effects estimation yielding a contribution of around 60 per cent.

<sup>&</sup>lt;sup>8</sup> We are grateful to Michael Weber for sharing sectoral data on frequency of price adjustment.

 $<sup>^{9}</sup>$  We report results using alternative measures of monetary policy shocks in Appendix L.

<sup>&</sup>lt;sup>10</sup> SVAR features industrial production, unemployment, consumer price index (CPI), commodity price index and the effective federal funds rate. The recursive Cholesky identification strategy is used with the effective federal funds rate ordered last. We estimate our SVAR using monthly data between 1969:1 and 2007:12 with twelve lags.

<sup>&</sup>lt;sup>11</sup> We use the publicly available data from Kuttner (2001) on monthly shocks identified as changes in current month's federal funds futures within daily windows around monetary policy announcements; the series is available on Kenneth Kuttner's website: https://econ.williams.edu/faculty-pages/research/. One disadvantage of this approach is that these shocks are only available from 1989:06 (and until 2007:12 for our purposes).

#### 4.1. Baseline specification

Our baseline econometric specification aims to estimate both full and (an upper bound of) the direct effect of a monetary shock on final consumption, and is based on horizon-specific analytical IRFs given in Corollaries 1 and 2. In particular, we adapt the local projection methodology of Jordà (2005) in order to estimate both full and direct effect at every horizon without assuming an underlying dynamic system.

First, in order to estimate the horizon-specific *full effect* of a monetary shock, we consider the following baseline specification:

$$\hat{c}_{k,t+H} = \phi_{k,H}^F r_t + \varepsilon_{k,t+H}^F, \qquad H = 1, 2, \dots, \overline{H}$$
(20)

where  $\hat{c}_{k,t+H} \equiv [c_{k,t+H} - c_{k,t+H}^*]$ ,  $\{c_{kt}\}_t$  being series of (log) final consumption in sector k, and  $\{c_{kt}^*\}_t$  is trend of (log) final consumption in sector  $k^{12}$ ;  $\{r_t\}_t$  is the monetary policy shock process;  $\varepsilon_{k,t+H}^F \equiv [\rho_{k,t}^F + e_{k,t+H}^F]$ , where  $\rho_{k,H}^F$  absorbs all unconditional means and unobserved time-invariant sectoral heterogeneity, whereas  $\{e_{kt}^F\}_t$  is the sector-specific error process; the coefficient  $\phi_{k,H}^F$  represents the horizon-H full effect of a monetary policy shock, and can be mapped back to the structural parameters of our model using Corollary 1.

Second, in order to estimate a horizon-specific (upper bound of) the direct effect, we use the following specification:

$$\hat{c}_{k,t+H} = \phi_{k,H}^{D} r_{t} + \sum_{\tau=1}^{H} \psi_{k,H}^{\tau} \sum_{r=1}^{K} \omega_{kr} \hat{c}_{r,t+H-\tau} + \varepsilon_{k,t+H}^{D}, \qquad H = 1, 2, \dots, \overline{H}$$
(21)

where  $\omega_{kr}$  is the share of sector k's expenditure on intermediate inputs that goes to sector r, corresponding to the [k, r] entry of the input-output matrix  $\Omega$ ; the rest of the notation follows that in (20). The coefficient  $\phi_{k,H}^D$  represents an upper bound of horizon-*H* direct effect of a monetary policy shock, whereas  $\psi_{k,H}^{\tau}$  measures the sensitivity of sectoral consumption at (t + H) to that of its suppliers at  $(t + H - \tau)$ ; both coefficients can be mapped back to the structural parameters of our model using Corollary 2.

Now given that  $\phi_{k,H}^{F}$  and  $\phi_{k,H}^{D}$  represent, respectively, full and (upper bound of) direct effect of a monetary policy shock, it follows that  $[\phi_{k,H}^{F} - \phi_{k,H}^{D}]$  gives a *lower bound* of the *downstream effect* at horizon *H*, representing the contribution of production networks to the effect of a monetary policy shock on final consumption.

#### 4.2. Coefficient estimation

Our specification in (20) and (21) allows for different estimation strategies, depending on the degree of cross-sectional coefficient heterogeneity one is willing to consider.

On the one hand, we consider the case where one imposes  $\phi_{k,H}^i = \phi_H^i$ , k = 1, 2, ..., K,  $i \in \{F, D\}$ , leaving  $\rho_{k,H}^i$ ,  $i \in \{F, D\}$ , as a sector fixed effect. We then obtain  $\hat{\phi}_H^F$  and  $\hat{\phi}_H^D$  by Fixed Effects estimation, separately for every horizon, interpreting  $\left[\hat{\phi}_H^F - \hat{\phi}_H^D\right]$  as a lower bound of the downstream effect at horizon *H*, on average.<sup>13</sup> We can also allow for *specific* dimensions of cross-sectional heterogeneity under fixed effects estimation by adding interaction terms of the monetary shock with sector-specific characteristics; in particular, in Section 5.2 we add interactions with sectoral Calvo parameters and intermediates intensities, and compare the results with model-based predictions regarding cross-sectional heterogeneity in responses.

On the other hand, we also consider the case with full cross-sectional coefficient heterogeneity, which amounts to estimating (20) and (21) separately for every sector by OLS. Having obtained  $\hat{\phi}_{k,H}^F$  and  $\hat{\phi}_{k,H}^D$ , we then interpret  $\left[\hat{\phi}_{k,H}^F - \hat{\phi}_{k,H}^D\right]$  as a lower bound of the downstream effect in sector *k* at horizon *H*. This allows us to see whether or not the contribution of production networks to the effect of a monetary policy shock is disproportionally larger for some sectors. We also aggregate the sectoral responses using the empirical consumption weights  $\{\omega_{ck}\}_k$ , thus evaluating aggregate full, (upper bound of) direct and (lower bound of) downstream effects.

Our specifications in (20) and (21) are based on theoretical expressions for IRFs, derived under the assumption of a one-time exogenous monetary shock hitting a system, which is originally in steady state. In the data, however, shocks can arrive in any period and are hitting the system that is not necessarily in steady state. In order to more closely mimic the theoretical environment in our estimation, we add a vector of controls  $\mathbb{X}_{t}^{H}$  to the right-hand side of both (20) and (21). The vector of controls includes a vector of leads of the monetary shock  $\{r_{t+\tau}\}_{\tau=1}^{H}$ , a vector of lags of the dependent variable  $\{\hat{c}_{k,t-s}\}_{s=1}^{S}$ , as well as a vector of lags of the federal funds rate  $\{ffr_{t-q}\}_{q=1}^{Q}$ .<sup>14</sup>

<sup>&</sup>lt;sup>12</sup> We extract trends of sectoral final consumption by HP-filtering.

<sup>&</sup>lt;sup>13</sup> For inference purposes, we construct heteroskedasticity-and-autocorrelation consistent (HAC) standard errors, additionally allowing for clustering at both sector- and month-level.

<sup>&</sup>lt;sup>14</sup> Adding a vector of leads of the shock additionally corrects for possible autocorrelation in monetary shock series, as shown in Alloza et al. (2019); adding lags of the dependent variable and the federal funds rate parsimoniously controls for initial conditions before the shock arrives, and we set S = 1 and Q = 4.

(a) Responses to a 25bp tightening (without controls)

(b) Responses to a 25bp tightening (with controls)



**Fig. 1.** Final consumption response to 25bp tightening: full and direct effects (Detail level, 161 sectors). *Note*: panel (a) shows results of panel fixed effects estimation of (20) and (21), without adding controls, reported as IRFs following a 25bp monetary tightening; panel (b) reports results of panel fixed effects estimation of (20) and (21), with a vector of controls  $x_t^H = \{\{r_{t+\tau}\}_{t=1}^H, \{\hat{c}_{k,t-s}\}_{s=1}^1, \{f_{t-\tau}\}_{t=1}^4\}$  added, reported as IRFs following a 25bp monetary tightening. Shaded areas denote 90% confidence bands around the full effect. The downstream effect contribution is constructed as the difference between cumulative full and direct effects as a percentage of the cumulative full effect (all cumulation is over 42 months). All reported IRFs have been smoothed with a 3-period centered moving average filter, with the original non-smoothed impulse responses reported in Appendix I (downstream effect contribution is constructed using non-smoothed IRFs.)

#### 5. Baseline results: panel fixed effects estimation

#### 5.1. Average full and direct effects

In Panel (a) of Fig. 1 we report the horizon-specific full effect and (an upper bound of) the direct effect on sectoral consumption of a 25 basis points monetary tightening, obtained by panel fixed effects estimation of (20) and (21), without adding control variables. The black line represents the full effect impulse response function; as one can see, consumption actually rises at early horizons following the tightening, before reaching a trough of around -0.30 percentage points decline just after 30 months. As for the red line, which represents (an upper bound of) the direct effect impulse response function with no controls in estimation, it similarly exhibits a small increase immediately after the tightening, but eventually reaches a trough of approximately -0.15 percentage points. As argued earlier, the difference between the two impulse response functions gives a lower bound for the downstream effect coming from input-output linkages. We summarize the downstream effect contribution by looking at the difference between cumulative full and direct effects over 42 months following the shock, and conclude that input-output linkages contribute to at least 50 per cent of the cumulative full effect.

Panel (b) of Fig. 1 reports impulse response functions estimated with a vector of controls  $X_t^H$  added to both (20) and (21). As can be seen from the black line, adding controls essentially removes the "consumption puzzle" observed earlier, with the full impulse response function being close to and not significantly different from zero, before turning negative; as for the trough of the consumption response, it is reached at around 26 months and is -0.20 percentage points in magnitude. Turning to the direct effect, its "consumption puzzle" is also removed by adding controls, and the peak drop achieved is at -0.12 percentage points. Summarizing the downstream effect contribution by the difference between cumulative full and direct effects over 42 months following the shock, the input-output linkages contribute to at least 34 per cent of the cumulative full effect.

Given that adding controls helps to address the theoretically implausible "consumption puzzles" in average responses, for the rest of the paper we add the vector of controls in all exercises.

#### 5.2. The role of heterogeneous Calvo parameters and intermediates intensity

In this subsection we report results obtained when interactions of monetary shock with sectoral Calvo parameters ( $r_t \times \alpha_k$ ) and sectoral intermediates intensities ( $r_t \times \delta_k$ ) are added to the right-hand side of both (20) and (21). This allows us to test theoretical predictions regarding cross-sectional heterogeneities in the downstream effect. In particular, recall that Proposition 1 establishes that the downstream effect is, *ceteris paribus*, unambiguously larger for sectors with larger intermediates intensity; on the other hand, the degree of price rigidity has an ambiguous effect on the magnitude of the downstream effect.

(a) Cumulative full and direct effects across Calvos

(b) Cumulative downstream effects across Calvos



**Fig. 2.** Response heterogeneity to 25bp tightening across frequencies of price adjustment and intermediates intensities. **Note:** Fig. 2 shows results of panel fixed effects estimation of (20) and (21) with interaction terms  $r_t \times \alpha_k$  and  $r_t \times \delta_k$  added, as well as vector of controls  $\mathbb{X}_t^H = \{r_{t+1}\}_{\tau=1}^H, \{\hat{c}_{k,t-s}\}_{s=1}^1, \{fr_{t-q}\}_{q=1}^d\}$ ; panels (a) and (b) show cumulative full, direct and downstream effects for various values of the Calvo parameter, holding intermediates intensity fixed at its sample median value; panels (c) and (d) show cumulative full, direct are over 42 months.

Panel (a) of Fig. 2 shows estimated cumulative full and direct effects (over 42 months) following a 25bp tightening, for various degrees of price rigidity (while intermediates intensity is held fixed at its sample median value). As one can see, both cumulative full and direct effects become more negative as the frequency of price non-adjustment rises, although the full effect is estimated to be more sensitive to the Calvo parameter. As a result, the downstream effect, given by the difference between cumulative full and direct effects, is estimated to be larger in magnitude as the frequency of price non-adjustment rises, as is shown graphically in Panel (b) of Fig. 2. The latter suggests that empirically, the effect of higher price rigidity on being more forward-looking, and hence being more sensitive to expectations of future prices set by suppliers, dominates the effect of adjusting prices less frequently and hence being less sensitive to current and expected future marginal costs.

Panel (c) of Fig. 2 shows estimated cumulative full and direct effects (over 42 months) following a 25bp tightening, for various intermediates intensities (while the Calvo parameter is held fixed at its sample median value). The results suggest that both cumulative full and direct effects become more negative as the intermediates intensity rises, although the full effect is estimated to be more sensitive to intermediates intensity. As a result, the downstream effect is estimated to be larger in magnitude as intermediates intensity rises, as is shown graphically in Panel (d) of Fig. 2. The latter is fully consistent with our theoretical predictions.



(b) Cumulative downstream effect across years



**Fig. 3.** Cumulative response to 25bp tightening across years: the role of time variation in intermediates intensity. *Note*: panels (a) and (b) show time series of cumulative (over 42 months) full and downstream effects, aggregated using sectoral consumption shares, under sectoral values of intermediates intensities across the years, as constructed by Ghassibe (2020), using estimation of (20) and (21) with controls either just linear interactions  $r_t \times \alpha_k$  and  $r_t \times \delta_k$  added, as well as with the addition of quadratic interaction terms  $r_t \times \alpha_k^2$ ,  $r_t \times \delta_k^2$ ,  $r_t \times \alpha_k \delta_k$ ; solid lines use true intermediates intensities available between 1987-2017, dotted lines show results using interpolated values of intermediates intensities constructed for 1963-1986 under the additional assumption of sectoral labor shares of value added fixed at their values in 1987. Shaded bars represent NBER recession dates.

In this subsection we have examined *linear* relationships between consumption responses and the degrees of price rigidity and intermediates intensity. However, Proposition 2 suggests that the relationship may be non-linear. In order to account for potential non-linearities, in Appendix J we report results under additional non-linear interaction terms  $r_t \times \alpha_k^2$ ,  $r_t \times \delta_k^2$ and  $r_t \times \alpha_k \delta_k$  added. The results suggest our findings regarding cross-sectional heterogeneity remain true even once nonlinearities have been allowed for.

#### 5.3. Time variation in intermediates intensity

Results in the previous subsection use values of sectoral intermediates intensities  $\delta_k$  based on the 2007 BEA "Use" tables at the Detail level. Accounts at such high level of disaggregation are not available at annual (or higher) frequency over time, but Ghassibe (2020) constructs annual measures of intermediate intensity for less disaggregated 65 sectors of the US economy between 1987–2017, with a possibility of extending the measures back to 1963 under additional assumptions regarding the labor share of value added.<sup>15</sup> Further, it is shown that intermediates intensities are strongly procyclical.

Estimates in Panels (c) and (d) of Fig. 2 give us the (cumulative) full, direct and downstream effect for various values of intermediates intensity, holding fixed the degree of price rigidity. In this subsection we combine those estimates with the annual data on intermediates intensities to perform the following exercise: for every sector, we compute the implied (cumulative) full, direct and downstream effect under its intermediates intensity in year t, t = 1963, 1964, ..., 2017. We then aggregate the sectoral effects to gauge the aggregate (cumulative) full, direct and downstream effects following a 25bp tightening in a particular year.

Fig. 3 shows cumulative (over 42 months) full and downstream effects following a 25bp tightening, between 1963-2017. We report results based both on the specification with only linear interactions with Calvo parameter and intermediates intensity, as well as the specification that additionally includes second-order interaction terms. First, note that in both specifications, the magnitude of both full and downstream effects is procyclical, which in term comes from the procyclicality of intermediates intensity. Such results provide a possible rationalization for the procyclical magnitude of GDP response to a monetary shocks documented by Tenreyro and Thwaites (2016) among others. Second, the observed procyclicality is substantially more pronounced in the non-linear specification, particularly in the Volcker disinflation episode, which witnessed a substantial drop in intermediates intensity; such empirical result suggests that the strength of monetary transmission to GDP can fall especially quickly in strong recessions which are associated with much smaller reliance on intermediate inputs.

<sup>&</sup>lt;sup>15</sup> Prior to 1987, BEA KLEMS accounts do not report sectoral employee compensation separately from sectoral value added; hence in order to construct sectoral intermediates intensities between 1963-1986 is it assumed the sectoral labor share of value added is fixed at its 1987 level.

(b) Aggregated Full and Direct Impulse Responses



(a) Sectoral Full Impulse Responses

(c) Histogram of cumulative Full and Direct Sectoral Effects



(d) Histogram of cumulative Downstream Effects



**Fig. 4.** Sector-level consumption responses to 25bp tightening (Detail level, 161 sectors). **Note**: panel (a) shows results of sector-by-sector OLS estimation of (20) with controls, reported as sector-level IRF following a 25bp monetary tightening; panel (b) reports results of aggregation of sector-level full and direct effects using empirical final consumption shares { $\omega_{ck}$ }  $|_{k=1}^{161}$ ; panels (c) and (d) report histograms of cumulative (over 42 months) sectoral full and direct effects, as well as the corresponding sectoral cumulative downstream effects. In panel (b) the reported impulse responses have been smoothed with a 3-period centered moving average filter, with the original non-smoothed impulse responses reported in Appendix I.

#### 6. Baseline results: sector-by-sector OLS estimation

#### 6.1. Sectoral responses and aggregation

Fig. 4 summarizes the results of sector-by-sector OLS estimation of both (20) and (21), yielding sectoral full and (upper bound of) direct impulse response functions. The latter are then aggregated in order to gauge economy-wide effects.

Panel (a) of Fig. 4 shows the full effect impulse response functions to a 25 basis points tightening for all 161 sectors in our baseline sample. Several aspects are worth highlighting. First, there is significant heterogeneity in the responses; given that our model predicts that sectoral responses are pinned down by, among other things, sectoral Calvo parameters and intermediates intensities, such dispersion in magnitudes of responses in consistent with large cross-sectional differences in frequencies of price adjustment, as documented by Nakamura and Steinsson (2008) and Gorodnichenko and Weber (2016) among others, as well as large heterogeneity in intermediates intensities, as is documented in Appendix G. Second, the aggregated response obtained by weighing individual responses by their respective consumption weights (solid black line) follows the aggregate real consumption response (dashed purple line) very closely, and considerably more closely than

the response obtained under aggregation using equal weights (dashed blue line). This suggests that the aggregate response may be driven by several large sectors, and hence that sectoral responses should indeed be aggregated with sectoral consumption weights, as opposed to equal weights.

Panel (b) reports the aggregated sectoral full effect (black line), as well as the aggregated (upper bound of) sectoral direct effects (red line), following a 25 basis points monetary tightening, where the aggregation performed with empirical consumption weights. As can be seen, the aggregated sectoral full effect is slightly positive at early horizons, but eventually reaches a trough of around -0.14 percentage points. Importantly, the aggregated full response follows very closely the impulse response of aggregate consumption, providing extra confidence in the new sectoral dataset that we have constructed. As for the aggregated (upper bound of) direct effect, it similarly starts with a slightly positive response, but then experiences a drop down to around -0.10 percentage points at the trough. When measured by the difference between cumulative aggregated full and direct effects (after 42 months), the downstream effect is estimated to contribute to (at least) 31 per cent of the cumulative full effect. The latter is very similar to the findings in the previous section under panel fixed effects estimation.

In Panels (c) and (d) we report histograms of sectoral cumulative full and (upper bounds of) cumulative direct effects (after 42 months), as well as sector-level cumulative downstream effects. One can see that the distribution of the sectoral full effects is shifted in the direction of more negative values compared to that of sectoral direct effects, which is consistent with the notion that the effect of monetary shocks on sectoral consumption is amplified by production networks; as for the sectoral downstream effects, those are estimated to be negative for the vast majority of sectors, confirming the finding that production networks amplify the effects of monetary shocks.

Note that although most of the results in this subsection are qualitatively in line with the predictions of our theory outlined in Section 2, two features cannot be reconciled using our baseline model. First, as can be seen in Panel (a) of Fig. 4, quite a number of sectors appear to be experiencing an increase in their consumption at certain horizons following a monetary tightening.<sup>16</sup> Second, as can be seen in Panel (d) of Fig. 4, though sector-level downstream effects are negative for the vast majority of sectors, it is actually positive for some sectors and thus production networks seem to actually attenuate, rather than amplify, the effect of monetary policy shocks on those sectors' consumptions.

To address this mismatch, in Appendix D we show that relaxing the assumption of unit elasticity of substitution across sectors can help jointly reconcile both of the two puzzles documented above (however, at the cost of analytical tractability at sector-level). This is because under non-unit elasticity of substitution, a sector's final consumption response is pinned down by the speed of its price response *relative* to the speed of adjustment of the aggregate consumption price index. Hence, if the sectoral goods are substitutes, following a monetary tightening the price index of the sectors with the highest speed of price adjustment drops much faster than the aggregate consumption price index, and hence those sectors can "steal" customers from other sectors and see an *increase* in their consumption; at the same time, sectors with the lowest speed of price adjustment can have their negative consumption price index, thus making them "lose" fewer customers to the other sectors. Crucially, however, the *aggregate* consumption response is fully independent of the elasticity of substitution across sectors; hence, although sectoral responses can exhibit different properties under non-unit elasticity of substitution, the aggregate consumption response is always negative following a monetary tightening and always amplified by networks regardless of the elasticity of substitution across sectors.

#### 6.2. Full and direct effects in broad sectoral groups

In order to gain further understanding of cross-sector heterogeneities in full and direct effects, in Fig. 5 we aggregate individual responses into 12 broad sectoral groups.

As before, we summarize the downstream effect by the difference between cumulative full and cumulative direct effects (over 42 months). By this metric, the group with the largest downstream effect is "Transportation and warehousing", followed by "Retail trade", "Information", "Agriculture, forestry, fishing and hunting" and "Professional and business services" as other groups with a substantial downstream effect. In fact, although those sectoral groups account for only 17 per cent of the aggregate consumption basket, their combined downstream effect equals 98 per cent of the aggregate downstream effect.

At the same time, "Other services including government" and "Arts, entertainment, recreation, accommodation, and food services" also exhibit downstream effects suggestive of amplification through production networks, though smaller in magnitude. As for "Educational services, health care, and social assistance", "Non-Durables manufacturing" and "Finance, insurance, real estate, rental and leasing" their downstream effect is essentially zero.

Notably, two sectoral groups with some of the largest full effects, namely "Mining and utilities" and "Durables manufacturing", exhibit a downstream effect of an inverted sign, implying that production networks actually slightly dampen their response to a monetary shock.

<sup>&</sup>lt;sup>16</sup> The latter is also found by Boivin et al. (2009) in their FAVAR study of product-level consumption responses.



**Fig. 5.** Consumption responses to a 25bp tightening across broad sectoral groups. **Note**: Fig. 5 shows results of sector-by-sector OLS estimation of (20) and (21) with controls, reported as sector-level direct and full IRFs following a 25bp monetary tightening that have been aggregated into broad sectoral groups using empirical consumption shares  $\{\omega_{ck}\}_{k=1}^{16}$ . The reported impulse responses have been smoothed with a 3-period centered moving average filter, with the original non-smoothed impulse responses reported in Appendix I.

#### 7. Further exercises and robustness checks

#### 7.1. Monte Carlo experiments

As argued earlier, our econometric specification allows to estimate the full effect of a monetary shock, as well as an *upper bound* for the direct effect, thus giving us a *lower bound* for the downstream effect. As an additional exercise, we apply our econometric specification to synthetic data generated by our model, calibrated to the same 161 sectors used in our baseline sample, and compare our estimated (lower bound of) downstream effect, to the true known contributions of linkages in the

#### Journal of Monetary Economics 119 (2021) 21-39



(c) Model with Taylor rule + CES aggregation

(b) Model with Taylor rule



(d) Model with Taylor rule + CES agg. + finite Frisch elasticity



**Fig. 6.** Theoretical full and direct effects, and those estimated from model-generated data. *Note*: Fig. 6 shows results of Monte Carlo experiments using simulations of log-linearized models fully outlined in Appendix A. In each exercise, we simulate 1,000 histories of calibrated model for 2,000 periods, discarding the first 1,748 periods as burn-in and only using the last T = 252 time periods (matching the time dimension of our sample), for the same 161 sectors used in our baseline sample, and apply specifications (20) and (21) (with controls) to estimate full and direct effects sector-by-sector with subsequent aggregation using empirical consumption weights; we then use the estimates to measure the downstream contribution to cumulative aggregated full effect, and compare it to the true known contribution in the model. In panel (a) we use our baseline model with money supply rule; in panel (b) we replace the money supply rule with the Taylor rule for the nominal interest rate; in panel (c) we additionally allow for CES aggregation across sectors with elasticity above one; in panel (d) we additionally allow for finite Frisch elasticity of labor supply.

model.<sup>17</sup> Panel (a) of Fig. 6 shows that based on means across simulations, our estimated downstream effect accounts for 41.02 per cent of the cumulative full effect (over 42 months), while the true contribution of linkages in the model equals 41.29 per cent; hence, the lower bound that our econometric strategy recovered from simulated data is very close to the true contribution.

Importantly, our econometric specification is based on sector-level analytical solutions to our model, which requires simplifying assumptions such as monetary policy based on a money supply rule, unit elasticity of substitution across sectors

<sup>&</sup>lt;sup>17</sup> We simulate 1,000 histories of log-linearized version of our model set out in Appendix A for 2,000 periods, discarding the first 1,748 periods as burnin and only using the last T = 252 time periods (matching the time dimension of our sample), and apply specifications (20) and (21) (with controls) to estimate full and direct effects sector-by-sector with subsequent aggregation using empirical consumption weights. We calibrate the model at monthly frequency, setting  $\beta = 0.9975$ ,  $\rho_r = 0.95$ ,  $\theta = 6$  and  $\sigma_r = 0.001$ , with input-output weights, sectoral Calvo parameters and intermediates intensities calibrated using data described in Section 3. In order to avoid possible singularities in the the simulated data, we include sector-specific i.i.d. productivity shocks  $\{\ln A_{kt}\}_t \sim^{iid} (0, \sigma_a^2)$ , where we set  $\sigma_a = 10^{-6} \times \sigma_r$ .

(a) Responses after a 25bp tightening: panel estimation

(b) Responses after a 25bp tightening: sector-by-sector estimation



Fig. 7. Final consumption response to 25bp tightening; full and direct effects under zero-diagonal (Detail level, 161 sectors). Note: Fig. 7 shows additional estimation of the direct effect using (21) where we force the diagonal elements of the input-output matrix to be equal to zero. The new estimates are reported alongside estimation of (20) and (21) without further restrictions. Panel (a) shows results using panel fixed effects estimation, whereas panel (b) shows results using sector-by-sector OLS estimation with subsequent aggregation using empirical consumption shares  $\{\omega_{ck}\}_{l=1}^{l-1}$ . The reported impulse responses have been smoothed with a 3-period centered moving average filter, with the original non-smoothed impulse responses reported in Appendix I.

and linear disutility of labor. Relaxing the above assumptions comes at the cost of sector-level analytical tractability. However, we can still assess the robustness of econometric strategy to model misspecification by applying it to synthetic data generated by alternative models.<sup>18</sup> In Panel (b) of Fig. 6 we show that when data is generated by a model with a Taylor rule<sup>19</sup>, we estimate the downstream effect contribution at 35.81 per cent of the cumulative full effect, while the true contribution is 30.38 per cent. In Panel (c) of Fig. 6 we additionally allow for elasticity of substitution across sectors equal to 2, the true contribution of linkages remains at 30.38 per cent, while we estimate it at 36.98 per cent. Finally, in Panel (d) of Fig. 6 we generate data additionally allowing for finite Frisch elasticity of labor supply equal to 0.5, which gives a true contribution of linkages equal to 43.54 per cent, while our specification estimates it at 41.86 per cent.

#### 7.2. Within-sector linkages vs. across-sector linkages

Our model allows for both within-sector and across-sector input-output linkages; however, our baseline econometric specification does not specifically estimate the downstream effect coming from across-sector linkages. In Fig. 7 we report results of an additional exercise which attempts to separate out the effects coming from the two types of linkages. In particular, we estimate (21) forcing diagonal elements of the input-output matrix to be equal to zero ( $\omega_{kk} = 0, \forall k$ ). If it was true that the majority of the downstream effect came from within-sector linkages, then the estimated direct effect under zero-diagonal matrix would coincide with the full effect; instead, we see in Fig. 7 that the downstream effect under zerodiagonal matrix is close to that under the true matrix. Our results therefore suggest that the majority of the downstream effect comes from across-sector linkages.

Importantly, however, in the previous exercise we forced a parameter inside a reduced-form econometric model, which is why our results should be treated with caution. As an additional robustness exercise, we separate out effects of within-sector versus across-sector linkages using our calibrated structural theoretical model.<sup>20</sup> In Fig. 8 we report aggregate consumption responses under three configurations: first, under input-output linkages completely switched off  $(\delta_k = 0, \forall k)$ , giving us the theoretical direct effect; second, under input-output matrix set equal to the identity matrix, so that we only allow for within-sector linkages, with alternative sectoral intermediates intensities  $(\overline{\delta}_k)$  given by the empirical share of variable costs that are paid to firms within own sector ( $\overline{\delta}_k \equiv \delta_k \omega_{kk}, \forall k$ ), giving us aggregate direct effect combined with the effect coming from own-sector linkages; third, under true  $\delta_k$  and  $\Omega$  for all sectors, giving us the theoretical full effect. As one can see, both in our baseline theoretical model, and in extensions featuring a Taylor rule, non-unit elasticity of substitution across sectors and finite Frisch elasticity, the direct effect combined with the effect of own-sector linkages is essentially indistinguishable

<sup>19</sup> We consider a Taylor rule of the form  $\frac{h}{l} = \left(\frac{h_{-1}}{l}\right)^{\rho_l} \left[ \left(\frac{p_l}{l_{l-1}^{\epsilon}}\right)^{\phi_{\pi}} \left(\frac{\zeta_l}{\zeta}\right)^{\phi_{\pi}} \left(\frac{\zeta_l}{\zeta_{l-1}}\right)^{\phi_{\pi}} \left(\frac{\zeta_l}{\zeta_{l-1}}\right)^{\phi_{\pi}} \right]^{1-\rho_l} e^{\mu_t}, \quad \mu_t = \rho_{\mu}\mu_{t-1} + \varepsilon_t^{\mu}, \quad \{\varepsilon_t^{\mu}\}_t \sim^{iid} (0, \sigma_{\mu}^2), \text{ where we set } \rho_i = 0.9, \phi_{\pi} = 1.24, \phi_c = 0.33/12, \phi_{gc} = 1.5, \rho_{\mu} = 0 \text{ and } \sigma_{\mu} = 0.000225.$ 

<sup>&</sup>lt;sup>18</sup> Appendix A outlines a generalized version of our model that relaxes the simplifying assumptions.

<sup>&</sup>lt;sup>20</sup> We use the same calibrations as outlined in Section 7.1



#### (a) Baseline model with money supply rule

(c) Model with Taylor rule + CES aggregation

(b) Model with Taylor rule

(d) Model with Taylor rule + CES agg. + finite Frisch elasticity



**Fig. 8.** Theoretical full and direct effects, and direct effects combined with own-sector linkages. *Note*: Fig. 8 shows aggregated full and direct effects from our calibrated theoretical model, as well effects from a calibration which only allows for within-sector input-output linkages, calibrated so that the sectoral intermediates intensities are equal to the empirical share of total variable costs that goes to intermediates bought from own sector (interpreted as direct effect+own linkages). The difference between the latter and the full effect is used to measure the (cumulative) downstream contribution without own-sector linkages. In panel (a) we use our baseline model with money supply rule; in panel (b) we replace the money supply rule with the Taylor rule for finite Frisch elasticity of labor supply.

from the direct effect. Therefore, our results using calibrated models also suggest that the majority of the downstream effect comes from across-sector linkages.

#### 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 econometric 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 at least 30 per cent of the effect of monetary policy shocks on US aggregate consumption comes from the amplification through input-output linkages. We also find that the network effect is larger, *ceteris paribus*, for sectors that adjust prices less frequently and those that rely more on intermediate inputs. Our results also suggest substantial concentration: sectors that jointly account for 17 per cent of our sample aggregate consumption account for 98 per cent of the amplification by production networks. Apart from the novel econometric evidence, we make two additional contributions. First, we obtain novel sector-level analytical solutions to a multi-sector New Keynesian models with asymmetric input-output linkages, and thus form a tractable econometric strategy. Second, we construct a new highly disaggregated monthly dataset for sectoral final consumptions in the US that can is consistent with sectoral classification used in input-output accounts of the US Bureau of Economic Analysis.

Our results create space for future research. First, our theoretical framework has only considered time-dependent pricing schedules following Calvo (1983); it would be an interesting agenda to additionally allow for state-dependent pricing and study, both theoretically an empirically, how firms with state-dependent and time-dependent pricing interact with each other in a production network, and what are the implications of such interaction for the response of aggregate variables to shocks of different magnitudes. Second, our paper has focused on production networks in a closed economy setting, and it would be an interesting extension to consider international production networks and their role in creating cross-border spillovers of monetary policy shocks.

#### Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jmoneco.2021.02. 002.

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