Inflation and GDP Dynamics in Production Networks: A Sufficient Statistics Approach

Hassan Afrouzi
Columbia University

Saroj Bhattarai
UT Austin

Indiana University
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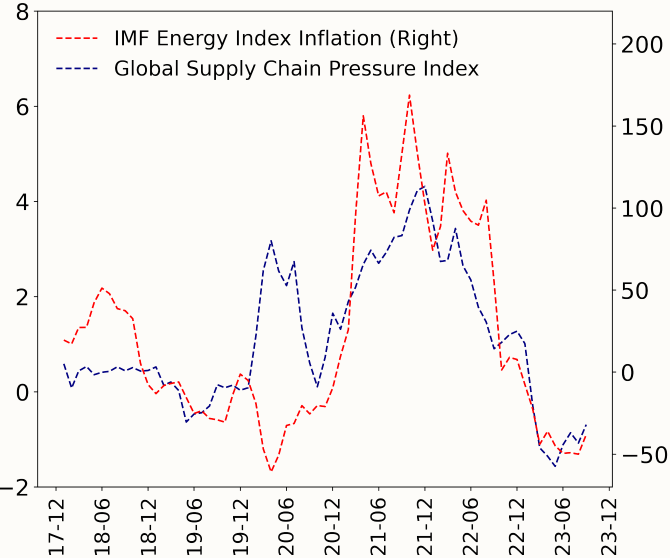
Introduction

Inflation Dynamics in Production Networks: Motivation



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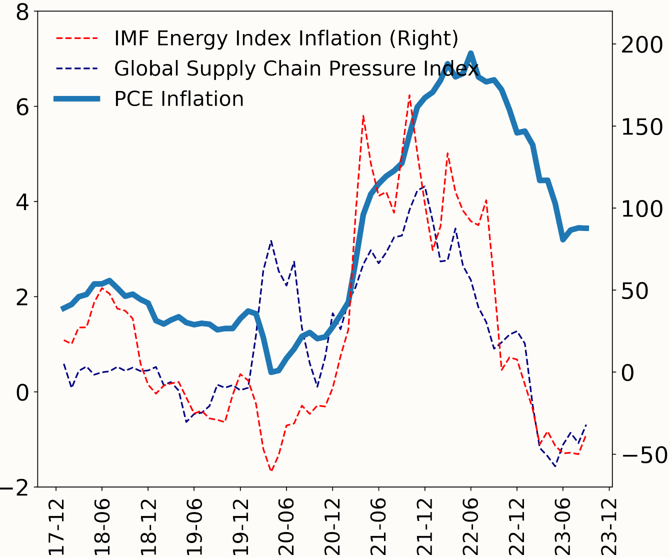

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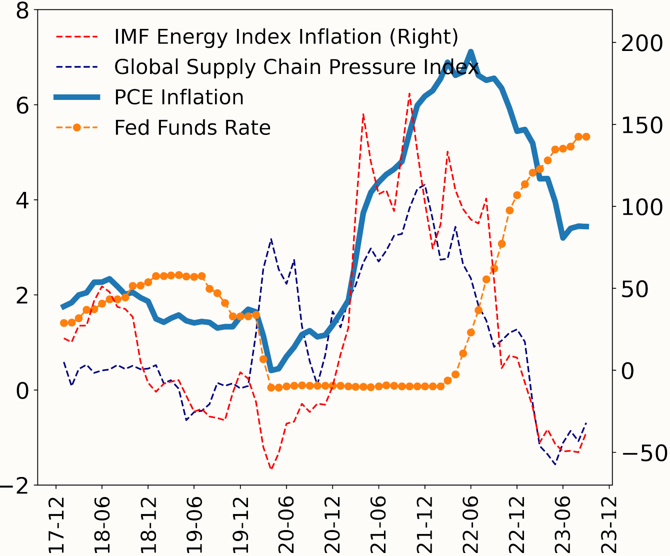

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- Accommodative monetary policy

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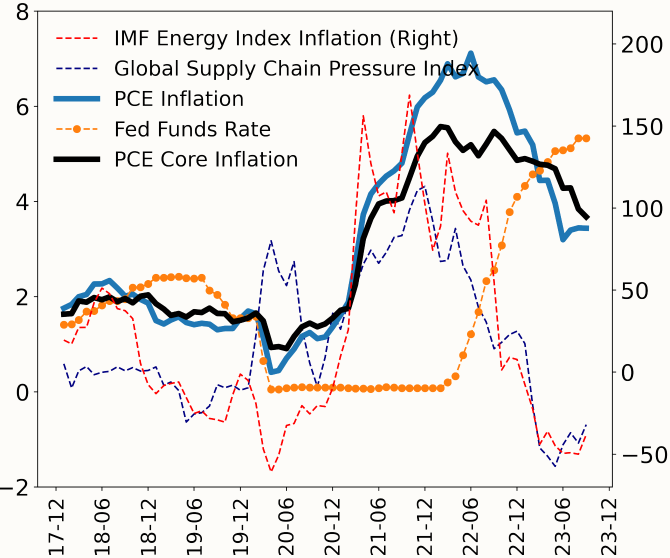

- Supply chain disruptions and commodity price booms
- Passthrough to headline inflation
- Accommodative monetary policy
- Slow and persistent rise of core inflation

Inflation Dynamics in Production Networks: What We Do

- Analytical solutions and **sufficient statistics** for inflation and GDP **dynamics** in production network economies with sticky prices
- Quantify how production networks affect the **size** and **persistence** of the economy's response to **monetary** and **sectoral TFP/wedge** shocks

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- Characterize the **disproportionate effect** of **network-adjusted** sticky sectors on inflation and GDP
- Analytical and quantitative analysis of **sectoral to aggregate inflation pass-through**

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- Characterize the **disproportionate effect** of **network-adjusted** sticky sectors on inflation and GDP
- Analytical and quantitative analysis of **sectoral to aggregate inflation pass-through**
- **Policy counterfacutal:** Stabilizing inflation driven by a **network-adjusted flexible price sector** leads to **contraction** in GDP *and* GDP gap

Literature

- Nominal frictions & I-O linkages: La'O and Tahbaz-Salehi (2022); Rubbo (2023); Lorenzoni and Werning (2023)
  - Analytical characterization of micro/macro dynamic propagation of both monetary and sectoral shocks
- I-O linkages and heterogeneity in price stickiness: Basu (1995); Carvalho (2006); Bouakez et al. (2009); Nakamura and Steinsson (2010); Pasten et al. (2020)
  - Unrestricted I-O structure and analytical solutions
- Macroeconomic implications of production networks and sectoral shocks: Acemoglu et al. (2012); Baqaee and Farhi (2020); Bigio and La'O (2020); Liu and Tsyvinski (2021)
  - Emphasis on interaction of production networks with price stickiness for the propagation of sectoral shocks

Model

Model–Description

- Time is continuous and runs forever
- n industries indexed by $i \in [n] \equiv \{1, \ldots, n\}$
- A measure of monopolistically competitive intermediate firms in each sector
- A final good producer in each sector packages and sells a sectoral good
- Sectoral goods consumed by household and used for production

Model

- **Household**

$$\max \int_0^{\infty} e^{-\rho t} \left[\ln(C_t) - L_t\right] \mathrm{d}t$$

$$\sum_{i \in [n]} P_{i,t} C_{i,t} + \dot{B}_t \leq W_t L_t + i_t B_t + T_t$$

$$C_t \equiv \Phi(C_{1,t}, \ldots, C_{n,t})$$

$$P_t \equiv \sum_{i \in [n]} P_{i,t} C_{i,t} / C_t$$

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- **Final Good** Producer

$$\max P_{i,t}Y_{i,t} - \int_0^1 P_{ij,t}Y^d_{ij,t}\mathrm{d}j \quad s.t.$$

$$Y_{i,t} = \left[\int_0^1 (Y^d_{ij,t})^{1-\sigma_i^{-1}}\mathrm{d}j\right]^{\frac{1}{1-\sigma_i^{-1}}}$$

Model–Intermediate Good Producers

- **Production**: Firm ij, $j \in [0, 1]$ produces with a CRS production function

$$Y^s_{ij,t} = Z_{i,t} F_i(L_{ij,t}, X_{ij,1,t}, \ldots, X_{ij,n,t})$$

- Arbirtrary production structure with aggregate and sectoral shocks

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- **Pricing**: In sector i, i.i.d. price changes arrive at Poisson rate $\theta_i > 0$
- A firm ij that gets to change its price at time t maximizes

$$\max_{P_{ij,t}} \int_0^\infty \theta_i e^{-(\theta_i h + \int_0^h i_{t+s} \mathrm{d}s)} [\underbrace{(1-\tau_{i,t}) P_{ij,t} \mathcal{D}(P_{ij,t}/P_{i,t+h}; Y_{i,t+h})}_{\text{total revenue at time } t} - \underbrace{\mathcal{C}_i(Y^s_{ij,t+h}; \mathbf{P}_{t+h}, Z_{i,t+h})}_{\text{total cost at time } t}] \mathrm{d}h$$

$$\text{subject to} \quad Y^s_{ij,t+h} \geq \mathcal{D}(P_{ij,t}/P_{i,t+h}; Y_{i,t+h}), \quad \forall h \geq 0$$

- Heterogeneous Calvo-type price stickiness across sectors

Theoretical Results

Log-linear Approximation around the Efficient Steady State

- **Desired Prices**

$$p^*_{i,t} \equiv \omega_{i,t} + mc_{i,t}$$

$$mc_{i,t} \equiv \alpha_i m_t + \sum_{k \in [n]} a_{ik} p_{k,t} - z_{i,t}$$

$$\omega_{i,t} \equiv \log\left(\frac{\sigma_i}{\sigma_i - 1} \times \frac{1}{1 - \tau_{i,t}}\right)$$

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- With I-O matrix $\mathbf{A} \equiv [a_{ik}] \in \mathbb{R}^{n\times n}$:

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- **Flex. price eq'm:** $\mathbf{p}^f_t \equiv \mathbf{p}_t = \mathbf{p}^*_t$

$$\mathbf{p}^f_t = m_t \mathbf{1} + \boldsymbol{\Psi}(\boldsymbol{\omega}_t - \boldsymbol{z}_t)$$

$$\boldsymbol{\Psi} \equiv (\mathbf{I} - \mathbf{A})^{-1} \quad \text{(inverse Leontief)}$$

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- **A** is a matrix of **strategic complementarities**

$$\mathbf{p}^*_t = (\mathbf{I} - \mathbf{A})\mathbf{p}^f_t + \mathbf{A}\mathbf{p}_t$$

Results–Sectoral Price Dynamics

- Log-linearize around the *efficient* steady state; stack log-prices in $\mathbf{p}_t \in \mathbb{R}^n$
- Let $\mathbf{A} = [a_{ij}] \in \mathbb{R}^{n \times n}$ be input-output matrix in the efficient steady-state
- If prices were flexible, then $\mathbf{p}_t = \mathbf{p}_t^f \equiv m_t \mathbf{1} + (\mathbf{I} - \mathbf{A})^{-1}(\boldsymbol{\omega}_t - \boldsymbol{z}_t)$

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Proposition: Log-linearized Price Dynamics

Sectoral prices $\mathbf{p}_t$ solve the following system of **sectoral Phillips curves**:

$$\dot{\boldsymbol{\pi}}_t = \rho \boldsymbol{\pi}_t + \boldsymbol{\Theta}^2(\mathbf{I} - \mathbf{A})(\mathbf{p}_t - \mathbf{p}_t^f) \quad \text{with BCs} \quad \mathbf{p}_0 = \mathbf{p}_{0^-}, \quad \|\mathbf{p}_t - \mathbf{p}_t^f\| \quad \text{bounded}$$

- $\boldsymbol{\Theta} = \text{diag}(\theta_i) \in \mathbb{R}^{n\times n}$ is diagonal matrix of frequencies of price adjustments
- $\boldsymbol{\Gamma} \equiv \boldsymbol{\Theta}^2(\mathbf{I} - \mathbf{A}) \in \mathbb{R}^{n\times n}$ is the **duration-adjusted Leontief matrix**

Results–Sectoral Price Dynamics: Remarks

$$\dot{\boldsymbol{\pi}}_t = \rho \boldsymbol{\pi}_t + \boldsymbol{\Gamma}(\mathbf{p}_t - \mathbf{p}_t^f), \qquad \boldsymbol{\Gamma} = \boldsymbol{\Theta}^2(\mathbf{I} - \mathbf{A})$$

- **$\boldsymbol{\Gamma}$ is the slope of sectoral Phillips curves in matrix form**
  - $\tilde{y}_t \equiv \beta'(\mathbf{p}_t^f - \mathbf{p}_t)$ is the **aggregate GDP gap**: (Aoki, 2001; Benigno, 2004)

$$\dot{\boldsymbol{\pi}}_t = \rho \boldsymbol{\pi}_t + \boldsymbol{\Gamma} \overbrace{(\mathbf{q}_t - \mathbf{q}_t^f)}^{\text{relative price gaps}} - \boldsymbol{\Gamma}\mathbf{1}\tilde{y}_t$$

  - $\mathbf{q}_t^f$ is mean zero, but there is dispersion within it (Lorenzoni and Werning, 2023)
- The Phillips curve uniquely determines the path of prices given a path for $\mathbf{p}_t^f$
- All shocks affect price dynamics *only* through $\mathbf{p}_t^f$

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- The Phillips curve uniquely determines the path of prices given a path for $\mathbf{p}_t^f$
  - Inflation adjusts so price gaps can close, with $\boldsymbol{\Gamma}$ capturing speed of adjustment
  - Why $\mathbf{I} - \mathbf{A}$? Those who adjust, do not adjust all the way (*not* inverse Leontief)
- All shocks affect price dynamics *only* through $\mathbf{p}_t^f$

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- All shocks affect price dynamics *only* through $\mathbf{p}_t^f$
  - General solution for any path of $\mathbf{p}_t^f$ in paper
  - IRFs to specific paths of shocks next

Results–Inflation and GDP IRFs to Monetary shocks

Corollary

Let $\rho = 0$. IRFs to a 1% one-time unanticipated permanent increase in m:

$$\mathbf{p}_t = (\mathbf{I} - e^{-\sqrt{\boldsymbol{\Gamma}}t})\mathbf{1} \qquad \text{(Sectoral Price IRFs)}$$

- Transition dynamics governed by the principal square root $\sqrt{\boldsymbol{\Gamma}}$

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$$\tilde{y}_t = m_t - p_t = \boldsymbol{\beta}^\intercal e^{-\sqrt{\boldsymbol{\Gamma}}t}\mathbf{1} \qquad \text{(GDP Gap IRF)}$$

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Results–Inflation and GDP IRFs to Sectoral Shocks

Corollary

Let $\mathbf{\Psi} \equiv (\mathbf{I} - \mathbf{A})^{-1}$. IRFs to a 1% (almost) permanent inflationary TFP/wedge shock to sector i are:

$$\mathbf{p}_t = (\mathbf{I} - e^{-\sqrt{\mathbf{\Gamma}}t})\mathbf{\Psi}\mathbf{e}_i \quad \text{(Sectoral Price IRFs)}$$

$$\boldsymbol{\pi}_t = \sqrt{\mathbf{\Gamma}}e^{-\sqrt{\mathbf{\Gamma}}\,t}\mathbf{\Psi}\mathbf{e}_i \quad \text{(Sectoral Inflation IRFs)}$$

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- Two separate roles of the Leontief matrix:
  - **Static** transmission through inverse Leontief ($\mathbf{e}_i \to \mathbf{\Psi}\mathbf{e}_i$)
  - **Dynamic** propagation through duration-adjusted Leontief ($\mathbf{\Psi}\mathbf{e}_i \to e^{-\sqrt{\mathbf{\Gamma}}t}\mathbf{\Psi}\mathbf{e}_i$)

Results–CIR of GDP Gap

Corollary

The cumulative impulse response (CIR) of GDP gap is given by

$$\begin{aligned}\text{CIR}_{\tilde{y}} &\equiv \int_0^\infty (y_t - y_t^f)\mathrm{d}t \\ &= \underbrace{\boldsymbol{\beta}^\intercal \sqrt{\mathbf{\Gamma}}^{-1}\mathbf{1}}_{\text{response to monetary shock}}, \quad \underbrace{\boldsymbol{\beta}^\intercal \sqrt{\mathbf{\Gamma}}^{-1}\mathbf{\Psi}\mathbf{e}_i}_{\text{response to TFP/wedge shock in sector } i}\end{aligned}$$

- General result on a summary statistic for monetary non-neutrality
- **Persistence of inflation** reflected in effects on GDP gap for both shocks

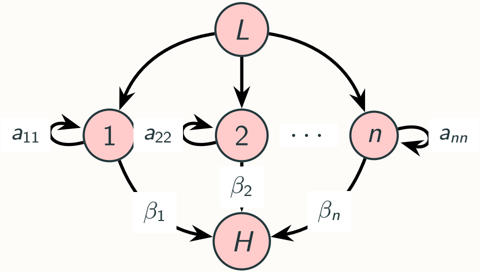
Unpacking $\sqrt{\Gamma}$: Local Expansion around Disconnected Economies

- Next we construct $\sqrt{\boldsymbol{\Gamma}}$ from the data and compute IRFs
- For example, the IRF of GDP gap to a monetary shock is of form

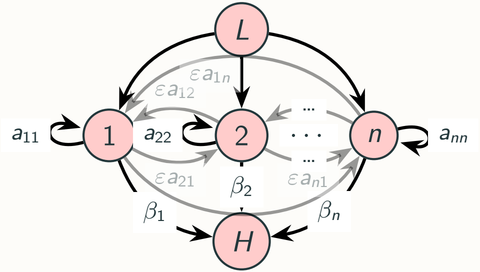
$$\tfrac{\partial}{\partial \delta_m} \tilde{y}_t = \boldsymbol{\beta}^\intercal e^{-\sqrt{\boldsymbol{\Gamma}} t} \mathbf{1} = \sum_{i=1}^{n} w_i e^{-d_i t}$$

  for some weights w_i and eigenvalues d_i.
- We want to connect w_i's and d_i's to the economic structure, but how?
- To interpret, expand towards an arbitrary network starting from a benchmark

Perturbation around Disconnected Economies

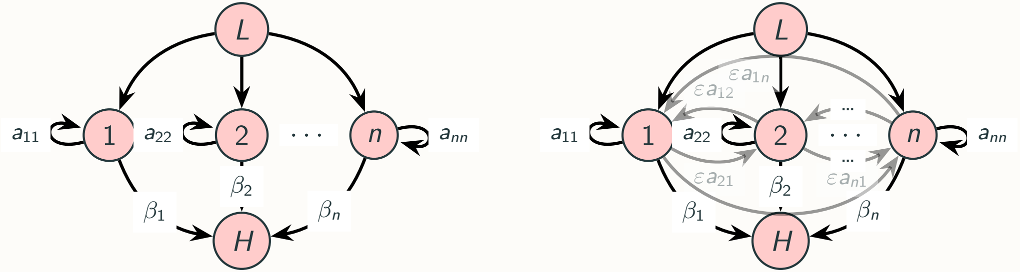


(a) *n*-Sector Disconnected Economies



(b) Perturbation towards $\mathbf{A} = [a_{ij}]$

Perturbation around Disconnected Economies



(a) *n*-Sector Disconnected Economies

(b) Perturbation towards $\mathbf{A} = [a_{ij}]$

Note

Study how persistence, non-neutrality, and pass-through change for small ε

- This is accurate quantitatively and now we can match eigenvalues to sectors

eigenvalues approx

Quantitative Results

Sufficient Statistics from Data

- Construct $\mathbf{\Gamma}$ and $\boldsymbol{\beta}$ using detailed sectoral U.S. data
  - Use the IO tables from BEA to construct IO linkages across sectors ($\mathbf{A}$); consumption expenditure shares ($\boldsymbol{\beta}$); and sectoral labor shares ($\boldsymbol{\alpha}$)
  - From 2012 at the detailed-level disaggregation (393 sectors)
- Construct the diagonal matrix $\mathbf{\Theta}^2$, whose elements are the squared frequency of price adjustment, using data from Pasten et al. (2020)

heat map

Aggregate Effects of a Monetary Shock

- Compute impulse response functions to a monetary shock
  - Shock size such that CPI inflation increases by 1 percent on impact
- Compare with a "horizontal" economy which only uses labor as input
  - Monetary non-neutrality 4.1 times higher
  - Persistence of CPI inflation higher (*strategic complementarity*)
- Compare with a "homogeneous frequency of price adjustment" economy
  - Monetary non-neutrality 2.4 times higher (*network-adjusted*-duration heterogeneity)
- Explore sectoral responses and role of network in detail

Figure 2: Keep Frequencies Heterogeneous; go from $\mathbf{A} = 0 \to \mathbf{A}_{\text{data}}$

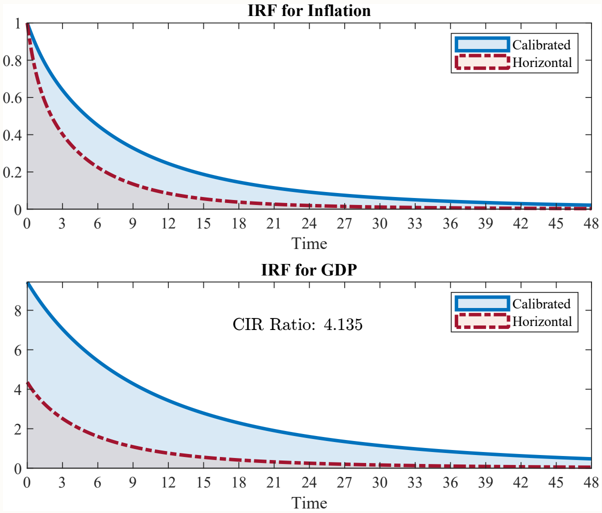
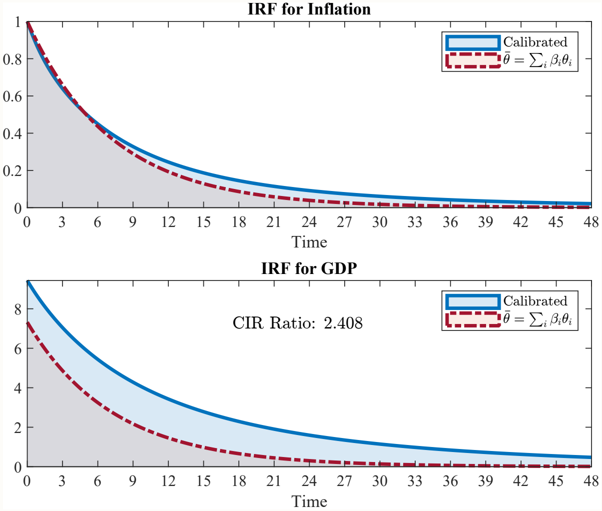
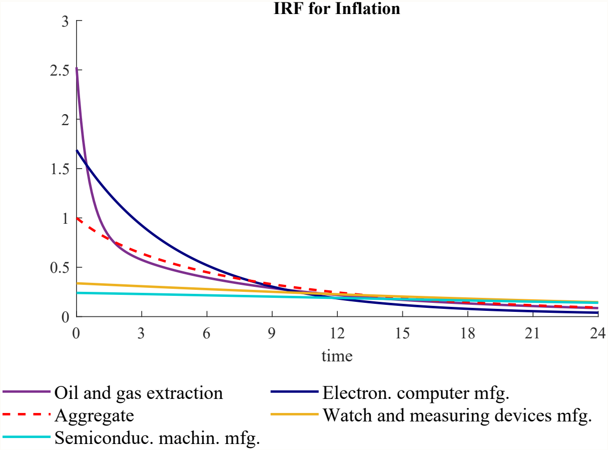


Figure 3: Keep Network Fixed; Go from Homogeneous Freq. to Heterogeneous Freq.



Distribution of Sectoral Responses to a Monetary Shock



Negative correlation between impact response and persistence ($d_i \approx \theta_i \sqrt{1 - a_{ii}}$)

detailed ranks

Network Effects on Monetary Non-Neutrality

- How does monetary non-neutrality change with input-output linkages?
  - Sectors have disproportionate roles based on their adjusted durations, $D_i \equiv 1/(\theta_i \sqrt{1 - a_{ii}})$

Monetary Non-Neutrality

Input-output linkages amplify monetary non-neutrality.

$$\text{CIR}_{\tilde{y},\delta_m} = \sum_{i=1}^{n} \underbrace{\beta_i D_i}_{\substack{\text{direct effect} \\ \text{of sector } i}} + \varepsilon \underbrace{\sum_{i=1}^{n} D_i \times \sum_{j \neq i}^{n} a_{ji} \times \frac{\beta_j}{1 - a_{jj}} \times \frac{D_i}{D_i + D_j}}_{\substack{\text{first-order indirect effect of} \\ \text{sector } i \text{ through network } \geq 0}} + \underbrace{\mathcal{O}(\|\varepsilon\|^2)}_{\substack{\text{higher-order} \\ \text{effects}}}$$

Disproportionate Effects of a Few Sectors

Table 1: Ranking of industries by eigenvalues in the disconnected economy

Industry	θ_i	$\theta_i\sqrt{1-a_{ii}}$	Eigenvalue $\sqrt{\Gamma}$
Insurance agencies, brokerages, and related act...	0.035586	0.022688	0.022439
Coating, engraving, heat treating and allied ac...	0.027804	0.02744	0.027327
Warehousing and storage	0.032407	0.030659	0.030562
Semiconductor machinery manufacturing	0.034003	0.032861	0.032858
Flavoring syrup and concentrate manufacturing	0.038897	0.038458	0.038413
Showcase, partition, shelving, and locker manuf...	0.039775	0.039335	0.039325
Packaging machinery manufacturing	0.040667	0.039349	0.039346
Machine shops	0.044323	0.043501	0.042797
Watch, clock, and other measuring and controlli...	0.043928	0.043682	0.043607

Counterfactual Exercise

Dropping the top three sectors reduces GDP CIR by 16 percent even though their expenditure share is zero.

Aggregate Effects of Sectoral Shocks

- Compute "pass-through" of sectoral shock inflation to aggregate inflation
  - Sectoral shock that increases sectoral inflation by 1% and lasts for T_s^i periods
  - Letting $D_i \equiv 1/(\theta_i \sqrt{1 - a_{ii}})$ be the adjusted duration of sector i:

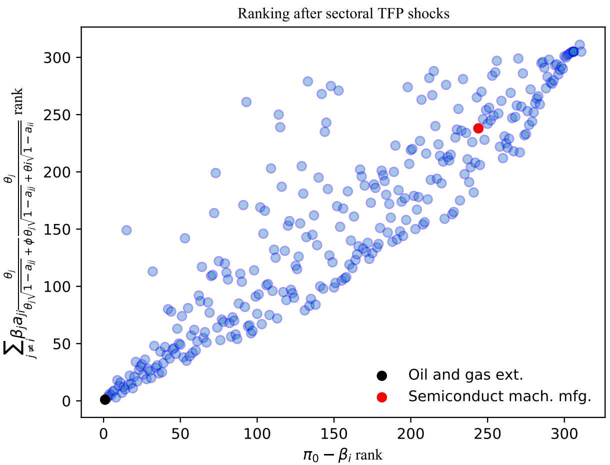
Aggregate Effects of Sectoral Shocks

Input-output structure amplifies the inflationary effects of sectoral shocks:

$$\frac{\partial}{\partial \varepsilon}\left[\left.\frac{\partial \pi_0}{\partial \pi_0^i}\right|_{\delta_z^i}\right] = \sum_{j \neq i} a_{ji} \times \underbrace{\frac{\beta_j}{1 - a_{jj}}}_{\text{Domar weight}} \times \underbrace{\frac{T_s^i}{T_s^i + D_j}}_{\text{shock/spell duration of } j} \times \underbrace{\frac{D_i}{D_i + D_j}}_{\text{relative stickiness of } i \text{ to } j}$$

Impact Pass-through to Aggregate Inflation

Figure 4: Correlation of actual and approximate ranks

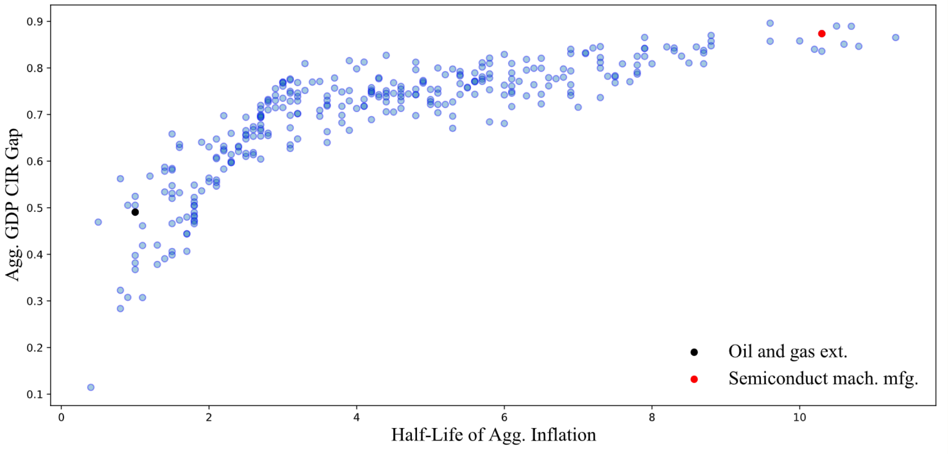


Effects on Aggregate GDP gap

- For aggregate GDP gap effects, impact pass-through to aggregate inflation not informative
- What matters is the *persistence* in aggregate inflation due to sectoral shocks
- Persistence is determined by transition dynamics in the model
- Duration-adjusted Leontief matrix summarizes all dynamics

Again, Persistence Really Matters

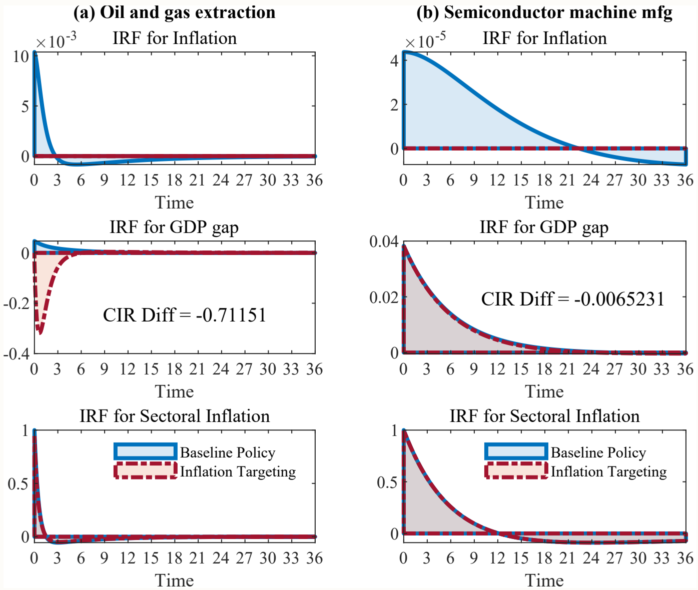
Figure 5: Correlation of aggregate GDP gap with half-life of inflation

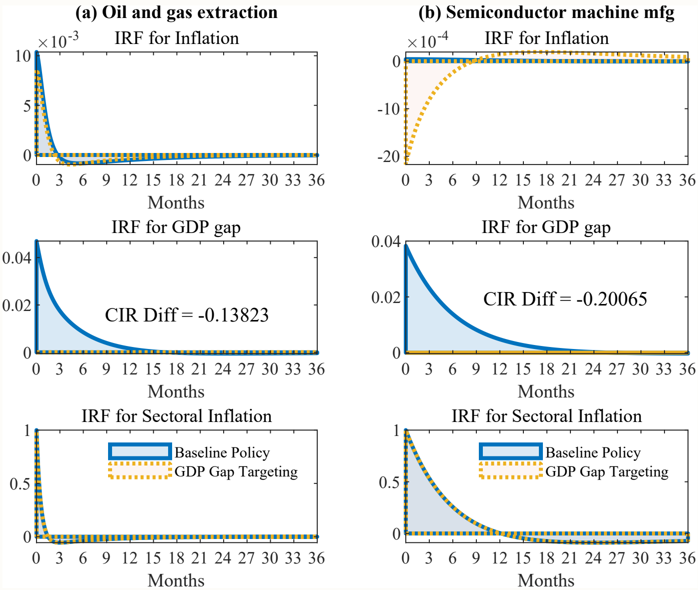


Endogenous Monetary Policy

- So far, considered monetary policy and sectoral shocks separately
- How does *endogenous* monetary policy change sectoral shock transmission?
- Baseline monetary policy equivalent to keeping nominal rates constant
- Now compare it with strict *CPI inflation targeting* and *GDP gap targeting*
- Recall stabilizing inflation $\neq$ stabilizing GDP gap:

$$\dot{\pi}_t = \rho \pi_t + \boldsymbol{\beta}^\intercal \boldsymbol{\Gamma}(\mathbf{q}_t - \mathbf{q}_t^f) - \boldsymbol{\beta}^\intercal \boldsymbol{\Gamma} \mathbf{1} \tilde{y}_t$$


(a) Oil and gas extraction
IRF for Inflation
×10^-3
10
5
0
0 3 6 9 12 15 18 21 24 27 30 33 36
Time
IRF for GDP gap
0
-0.2
-0.4
CIR Diff = -0.71151
0 3 6 9 12 15 18 21 24 27 30 33 36
Time
IRF for Sectoral Inflation
1
0.5
0
Baseline Policy
Inflation Targeting
0 3 6 9 12 15 18 21 24 27 30 33 36
Time
(b) Semiconductor machine mfg
IRF for Inflation
×10^-5
4
2
0
0 3 6 9 12 15 18 21 24 27 30 33 36
Time
IRF for GDP gap
0.04
0.02
0
CIR Diff = -0.0065231
0 3 6 9 12 15 18 21 24 27 30 33 36
Time
IRF for Sectoral Inflation
1
0.5
0
Baseline Policy
Inflation Targeting
0 3 6 9 12 15 18 21 24 27 30 33 36
Time


(a) Oil and gas extraction
(b) Semiconductor machine mfg
IRF for Inflation
×10-3
×10-4
IRF for GDP gap
CIR Diff = -0.13823
CIR Diff = -0.20065
IRF for Sectoral Inflation
Baseline Policy
GDP Gap Targeting
Months

Extensions

- Finite Frisch elasticity
- Taylor rule as monetary policy
- Aggregate Phillips curve and slopes
- IO matrix measurement at a more aggregated level

Conclusion

Conclusion

- Sufficient statistics for dynamics with sticky prices and production networks
- **Persistence** of aggregate inflation is key for aggregate propagation of shocks
- Real effects of monetary policy are amplified by input-output linkages
    - Quantitatively relevant in a calibrated U.S. economy
    - **Some** sectors play a major role
- Stabilizing inflation in response to sectoral shocks can have different implications based on the originating sector
- Future work
    - Optimal policy
    - Menu costs

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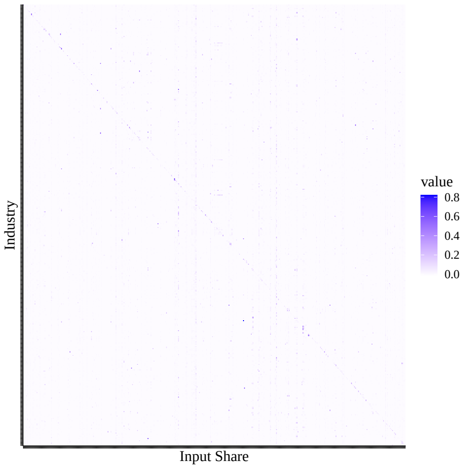

Figure 6: U.S. sectoral input-output matrix (heat map) in 2012

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Figure 7: Eigenvalues in the disconnected economy and the baseline economy.

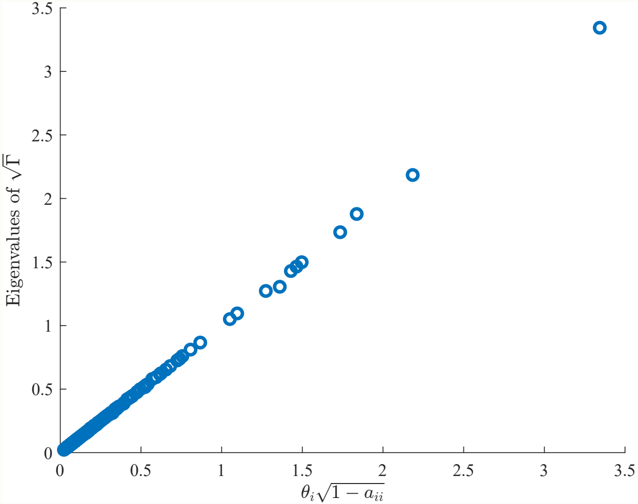

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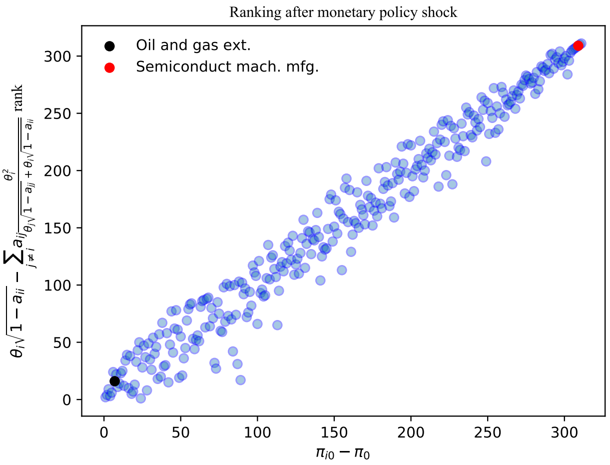
Figure 8: Correlation of actual and approximate ranks



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