

Business Cycles with Pricing Cascades

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The views expressed here are the responsibility of the authors only, and do not necessarily coincide with those of the ECB or the Eurosystem.

Motivation

- Recent events have brought new evidence regarding the drivers and dynamics of inflation:

- i Possibility of **large inflationary swings** in advanced economies

► Show

Challenge: *NKPC with a realistic slope requires implausibly large shocks* (L'Huillier and Phelan, 2024)

- ii Fluctuations in the **frequency of price adjustment** (Montag and Villar, 2023; Cavallo et al., 2024)

► Show

Challenge: *a fixed menu cost model matches that at the cost of an implausibly steep NKPC* (Blanco et al., 2024)

- iii Importance of **sector-specific** drivers of inflation (Schneider, 2023; Rubbo, 2024)

► Show

Challenge: *need to allow for large sector-specific shocks in a setting with menu costs*

- Develop a **dynamic quantitative** general equilibrium model that features: a number of **sectors interconnected by networks** with **state-dependent pricing** that is solved **fully non-linearly**

New cyclical mechanism: interaction of **networks** and pricing **cascades**

- **Interaction** of our model ingredients creates pricing **cascades**: large movements in aggregates trigger additional price adjustment decisions at the extensive margin
- **Demand shocks** **Networks slow down** the extensive margin adjustment: **cascades dampening**
 - i Networks slow down the desired price changes, hence firms are less willing to pay the cost of adjustment
 - ii Quantitatively, delivers a "global flattening" of the Phillips Curve, implying strong monetary non-neutrality even following very large shocks
- **Supply shocks (Agg./sectoral)** **Networks speed up** the extensive margin adjust.: **cascades amplification**
 - i Networks amplify the desired price changes, hence firms are more willing to pay the cost of adjustment
 - ii Quantitatively, creates frequency increases and inflationary spirals following aggregate TFP/markup shocks, or TFP/markup shocks to sectors that are **major and concentrated** suppliers to the rest of the economy

MODEL

Model overview

- **Timing:** infinite-horizon setting in discrete time, indexed by $t = 0, 1, 2, \dots$
- **Households:** continuum of identical households; consume output and supply labor
- **Firms:** continuum of monopolistically competitive firms, each belongs to one of N sectors, indexed $i \in \{1, 2, \dots, N\}$; there is a measure one of firms in each sector
- **Factors:** firms use labor and intermediate inputs purchased from other firms
- **Government Policy:** central bank sets the level of money supply M_t

Households

- The representative household maximizes expected lifetime utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t [\log C_t - L_t]$$

subject to a standard budget constraint

- Households are also subject to a **cash-in-advance** constraint: $P_t^C C_t \leq M_t$

- Aggregate consumption: $C_t = \iota^C \prod_{i=1}^N C_i^{\bar{\omega}_i^C}$, $\sum_{i=1}^N \bar{\omega}_i^C = 1$, $\bar{\omega}_i^C \geq 0, \forall i$

- Sectoral consumption: $C_{i,t} = \left\{ \int_0^1 [\zeta_{i,t}(j) C_{i,t}(j)]^{\frac{\epsilon-1}{\epsilon}} dj \right\}^{\frac{\epsilon}{\epsilon-1}}$, $\epsilon > 1$

where $\zeta_{i,t}(j)$ is a **firm-level quality** process:

$$\log \zeta_{i,t}(j) = \log \zeta_{i,t-1}(j) + \sigma_i \varepsilon_{i,t}(j)$$

Firms: production

- Any firm j in sector i has access to the following production technology:

$$Y_{i,t}(j) = \frac{1}{\zeta_{i,t}(j)} \times A_{i,t} \times L_{i,t}(j)^{\bar{\alpha}_i} \prod_{k=1}^N X_{i,k,t}(j)^{\bar{\omega}_{ik}},$$

where $A_{i,t}$ is a **sectoral productivity** process, $L_{i,t}(j)$ is firm-level labor input, $X_{i,k,t}(j)$ is firm-level intermediate input demand for sector k 's goods and $\bar{\alpha}_i + \sum_{k=1}^N \bar{\omega}_{ik} = 1$, $\bar{\alpha}_i \geq 0, \bar{\omega}_{ik} \geq 0, \forall i, k$

- Cost-minimization delivers the following marginal cost:

$$MC_{i,t}(j) = \zeta_{i,t}(j) \times \frac{1}{A_{i,t}} \times w_t^{\bar{\alpha}_i} \prod_{k=1}^N p_{k,t}^{\bar{\omega}_{ik}}.$$

Firms: pricing

- Price resetting involves paying a sector-specific **menu cost** $\kappa_{i,t}$ measured in labor hours

- Let $p_{i,t}(j) \equiv \log \tilde{P}_{i,t}(j) = \log \frac{P_{i,t}(j)}{\zeta_{i,t}(j)M_t}$ be the quality-adjusted *log* real price

- The value of a firm in sector i that has set a quality-adjusted real price p :

$$V_{i,t}(p) = \tilde{D}_{i,t}(p) + \beta \mathbb{E}_t \left[\left\{ 1 - \eta_{i,t+1}(p - \sigma_i \varepsilon_{i,t+1} - m_{t+1}) \right\} \times V_{i,t+1}(\overbrace{p - \sigma_i \varepsilon_{i,t+1} - m_{t+1}}^{\text{"Eroded" real price}}) \right] \\ + \beta \mathbb{E}_t \left[\underbrace{\eta_{i,t+1}(p - \sigma_i \varepsilon_{i,t+1} - m_{t+1})}_{\text{Pr. of adjustment}} \times \left(\max_{p'} V_{i,t+1}(p') - \kappa_{i,t} \right) \right]$$

- Following Golosov and Lucas (2007), we assume the following **adjustment hazard** $\eta_{i,t}(\cdot)$:

$$\eta_{i,t}(p) = \mathbf{1}(L_{i,t}(p) > 0) = \mathbf{1} \left(\max_{p'} V_{i,t}(p') - V_{i,t}(p) > \bar{\kappa}_i \right)$$

STATIC SETUP

Intuition in a simplified setup

- Consider the static limit of the model ($\beta = 0$) and focus on the initial time period ($t = 0$)
- For a firm j in sector i , the real profit gain from price adjustment satisfies:

$$\tilde{D}_i^*(j) - \tilde{D}_i(j) \propto [\tilde{p}_i(j)]^2$$

where $\tilde{p}_i(j) \equiv \log \tilde{P}_i(j) - \log \tilde{P}_i^*$ is the firm-level real **price gap**

- The real sectoral optimal reset price is $\tilde{P}_i^* \equiv P_i^*/M = \frac{1}{A_i} \prod_k \tilde{P}_k^{\bar{\omega}_{ik}}$, hence normalizing $\sigma_i = 1$:

$$\tilde{p}_i(j) = \underbrace{-\varepsilon_i(j) - m}_{\text{"Erosion"}} + \underbrace{a_i - \sum_{k=1}^N \bar{\omega}_{ik} \log \tilde{P}_k}_{\text{Sectoral optimal reset price}}$$

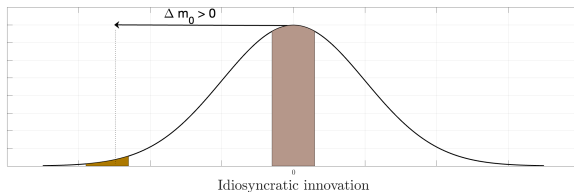
where m is money supply, a_i is sectoral TFP shock and $\log \tilde{P}_k \equiv (\log P_k - m)$ is real sectoral price

Monetary shock: cascades dampening by networks

- **Inaction region:** a firm will **not** adjust if it draws an innovation in

$$(\kappa_{i,t} = \bar{\kappa}_i [\tilde{P}_{i,t} / \tilde{P}_{i,t}^*]^{\epsilon-1} \lambda_{i,t})$$

$$[\underline{\varepsilon}_i, \bar{\varepsilon}_i] = -m - \sum_{k=1}^N \bar{\omega}_{ik} \log \tilde{P}_k \pm \sqrt{\frac{2\bar{\kappa}_i}{\epsilon-1}}$$



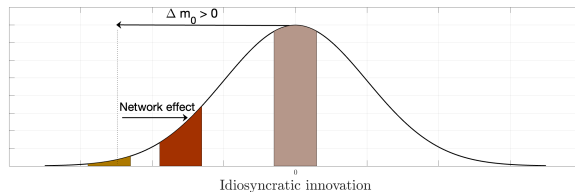
- **Incomplete monetary pass-through:** $\log \tilde{P}_k = (\log P_k - m) < 0, \forall k$

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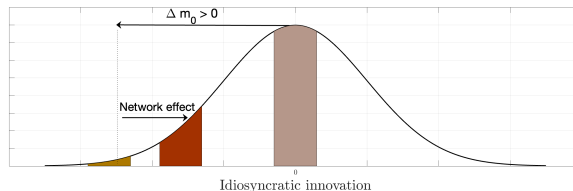
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- **Incomplete monetary pass-through:** $\log \tilde{P}_k = (\log P_k - m) < 0, \forall k$

Proposition (Cascades dampening: monetary shocks)

For a monetary shock $\mathbf{m}$, under incomplete pass-through, networks **lower the probability** of adjustment ϱ_i for any firm in any sector i , and the dampening increases in the sectoral **customer centrality** $\mathcal{C}_i$

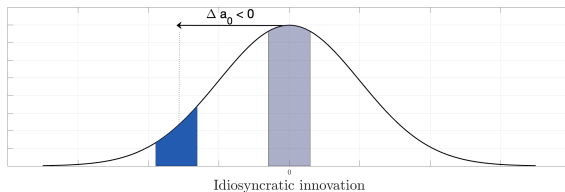
$$\Delta \sqrt{\varrho_i(\mathbf{m})} \propto \mathcal{C}_i \equiv \sum_{j=1}^N (I - \bar{\Omega})_{ij}^{-1} - 1$$

TFP shock: cascades amplification by networks

- **Inaction region:** a firm will **not** adjust if it draws an innovation in

$$(\kappa_{i,t} = \bar{\kappa}_i [\tilde{p}_{i,t} / \tilde{p}_{i,t}^*]^{\epsilon-1} \lambda_{i,t})$$

$$[\underline{\varepsilon}_i, \bar{\varepsilon}_i] = a_i - \sum_{k=1}^N \bar{\omega}_{ik} \log \tilde{p}_k \pm \sqrt{\frac{2\bar{\kappa}_i}{\epsilon-1}}$$



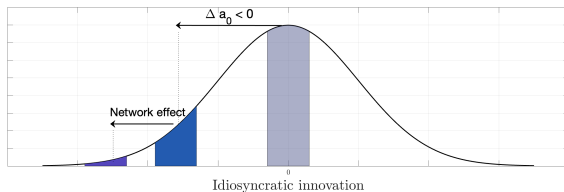
- **Inflationary TFP deterioration:** $\log \tilde{p}_k > 0, \forall k$

TFP shock: **cascades amplification** by networks

- **Inaction region:** a firm will **not** adjust if it draws an innovation in

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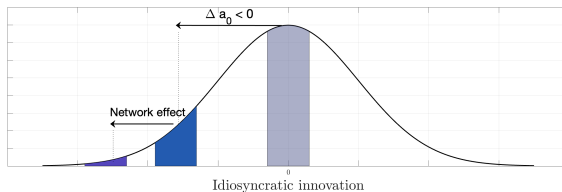
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- **Inflationary TFP deterioration:** $\log \tilde{P}_k > 0, \forall k$

Proposition (Cascades amplification: aggregate TFP shock)

For an aggregate TFP shock $\mathbf{a}$, under counter-moving sectoral prices, networks **increase the probability** of adjustment ϱ_i for any firm in any sector i , and the amplification increases in the sectoral **customer centrality** $\mathcal{C}_i$

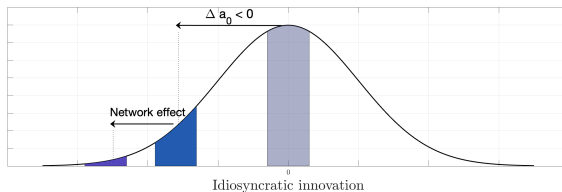
$$\Delta \sqrt{\varrho_i(\mathbf{a})} \propto \mathcal{C}_i \equiv \sum_{j=1}^N (I - \bar{\Omega})_{ij}^{-1} - 1$$

TFP shock: cascades amplification by networks

- **Inaction region:** a firm will **not** adjust if it draws an innovation in

$$(\kappa_{i,t} = \bar{\kappa}_i [\tilde{P}_{i,t} / \tilde{P}_{i,t}^*]^{\epsilon-1} \lambda_{i,t})$$

$$[\underline{\varepsilon}_i, \bar{\varepsilon}_i] = a_i - \sum_{k=1}^N \bar{\omega}_{ik} \log \tilde{P}_k \pm \sqrt{\frac{2\bar{\kappa}_i}{\epsilon-1}}$$



- **Inflationary TFP deterioration:** $\log \tilde{P}_k > 0, \forall k$

Proposition (Cascades amplification: sectoral TFP shock)

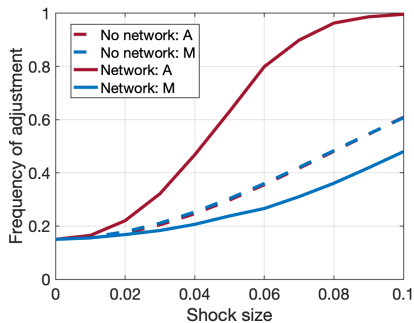
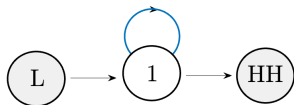
For a sectoral TFP shock $\mathbf{a}_i$, under counter-moving sectoral prices, average probab. of adjustment around symmetric s.s. is:

$$\bar{\varrho}(\mathbf{a}_i) \propto \mathcal{H}_i$$

where $\mathcal{H}_i$ is the sectoral **supplier Herfindahl**: $\mathcal{H}_i \equiv \left[\frac{1}{N} \sum_j (I - \bar{\Omega})_{j,i}^{-1} \right]^2 + \text{Var}(I - \bar{\Omega})_{(i)}^{-1}$.

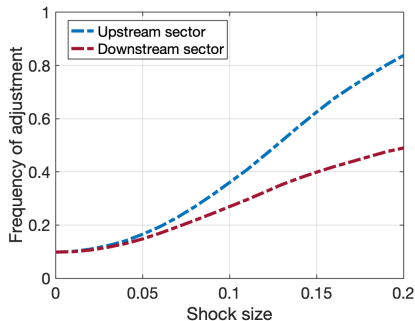
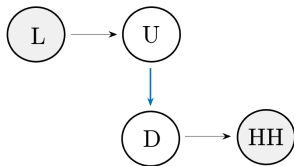
Toy example 1: roundabout production

- Marginal cost: $MC(j) = \zeta(j) \times \frac{1}{A} \times M^{\bar{\alpha}} p^{1-\bar{\alpha}}$



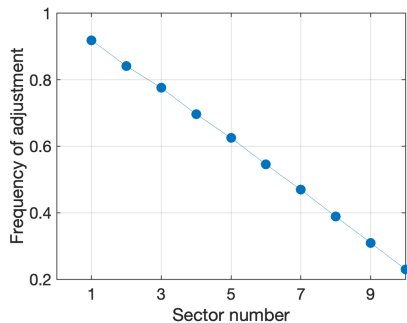
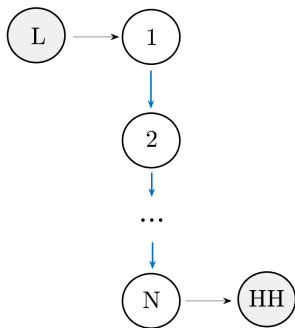
Toy example 2: two-sector vertical chain

- Marginal costs: $MC_U(j) = \zeta_U(j) \times \frac{1}{A_U} \times M$, $MC_D(j) = \zeta_D(j) \times \frac{1}{A_D} \times P_U$



Toy example 3: N -sector vertical chain

- Marginal costs: $MC_i(j) = \zeta_i(j) \times \frac{1}{A_i} \times P_{i-1}$



QUANTITATIVE RESULTS

Computation

- **Steady state:** solve the stationary Bellman equations and firms' price distribution on an evenly spaced grid of log quality-adjusted real prices for every sector
- Consider a **known** sequence of money supply $\{\Delta \log M_t\}_{t=0}^{\infty}$ and productivity $\{\log A_{k,t}\}_{t=0}^{\infty}$
- Assume that after a finite time period T the economy converges back to the stationary distribution
- From a guess for the sequences of aggregate and sectoral variables, follow **backward-forward iteration** until convergence:
 - ① Starting from $t = T$, iterate **backwards** to $t = 0$ to solve for the micro value functions
 - ② Starting from $t = 0$, iterate **forwards** to $t = T$ to solve for price distributions and aggregate numerically

Calibration (Euro Area, monthly frequency)

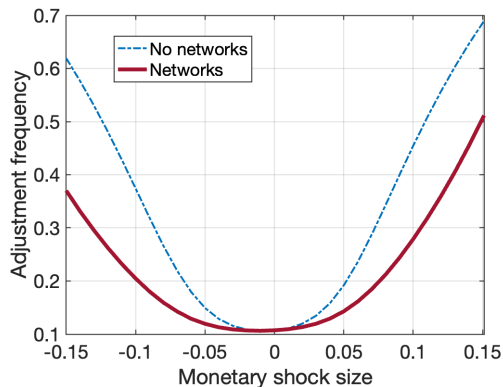
<i>Aggregate parameters</i>			
β	$0.96^{1/12}$	Discount factor (monthly)	Golosov and Lucas (2007)
ϵ	3	Goods elasticity of substitution	Midrigan (2011)
$\bar{\pi}$	0.02/12	Trend inflation (monthly)	ECB target
ρ	0.90	Persistence of the TFP shock	Half-life of seven months
<i>Sectoral parameters</i>			
N	39	Number of sectors	Data from Gautier et al. (2024)
$\{\bar{\omega}_i^C\}_{i=1}^N$		Sector consumption weights	World IO Tables
$\{\bar{\omega}_{ik}\}_{i,k=1}^N$		Sector input-output matrix	World IO Tables
$\{\bar{\alpha}_i\}_{i=1}^N$		Sector labor weights	World IO Tables
<i>Firm-level pricing parameters</i>			
$\{\bar{\kappa}_i\}_{i=1}^N$		Menu costs	Estimated to fit frequency, std dev.
$\{\sigma_i\}_{i=1}^N$		Std. dev. of firm-level shocks	of Δp from Gautier et al. (2024)

Monetary shocks

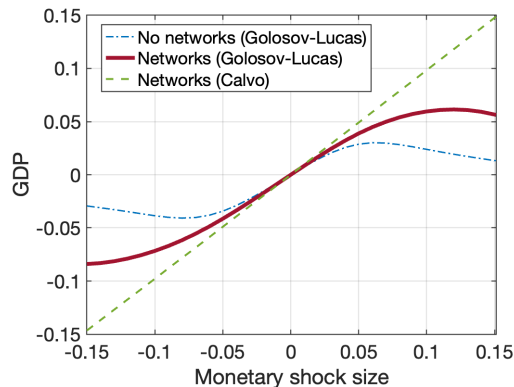
$$\log M_t = \bar{\pi} + \log M_{t-1} + \varepsilon_t^M$$

Cascades dampening following monetary shocks

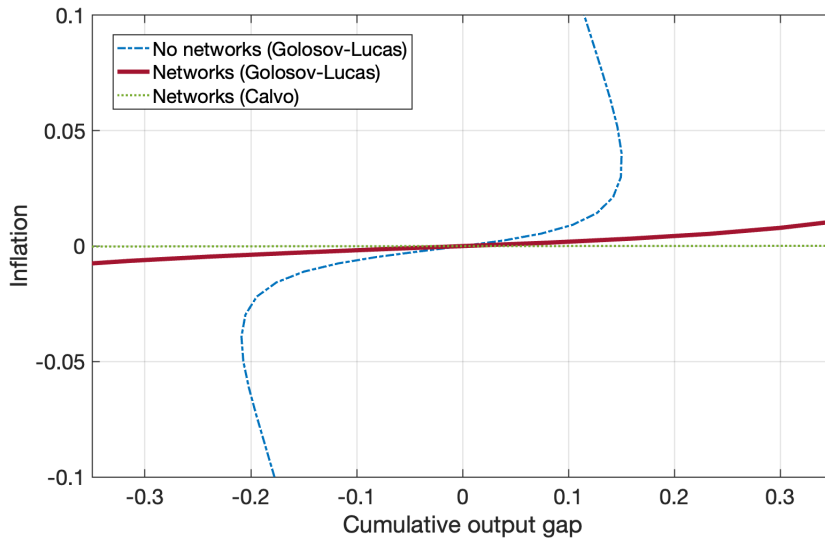
(a) Aggregate adjustment frequency



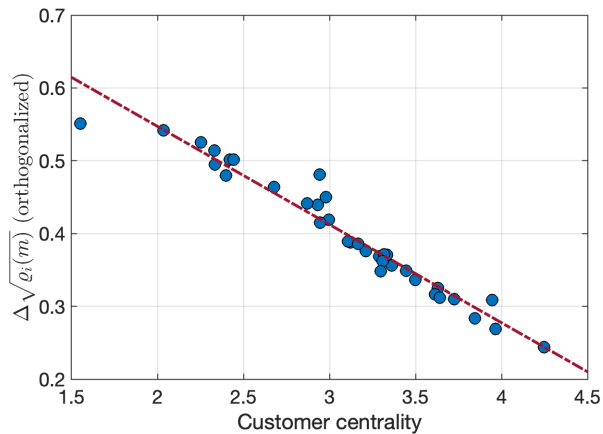
(b) GDP



Non-linear Phillips Curves



Sectoral frequency responses vs. Customer Centrality

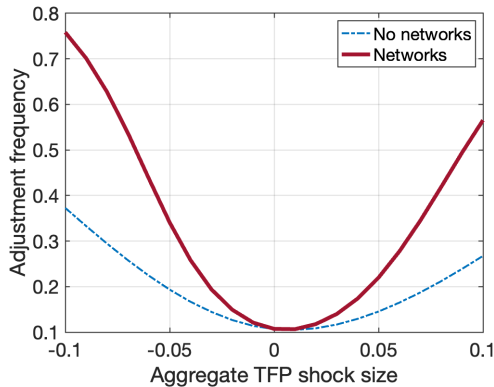


Aggregate TFP shocks

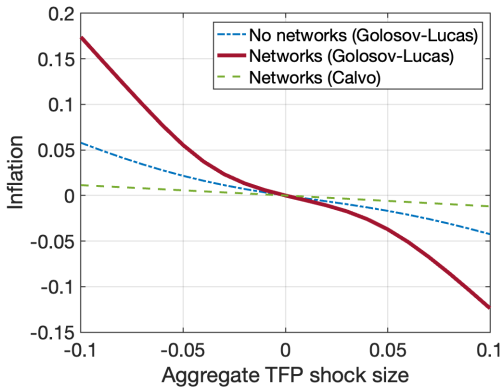
$$\log A_t = \rho \log A_{t-1} + \varepsilon_t^A$$

Cascades amplification following TFP shocks

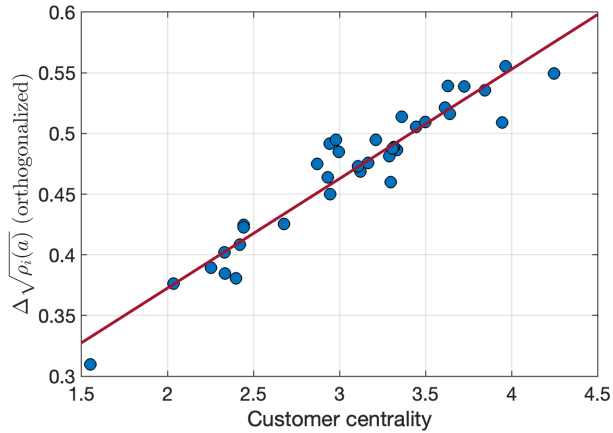
(a) Aggregate adjustment frequency



(b) CPI inflation

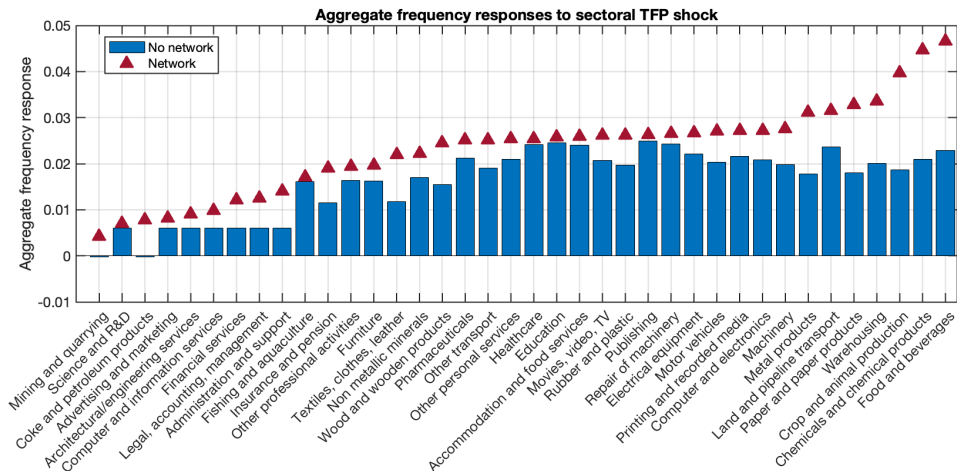


Sectoral frequency responses vs. Customer Centrality



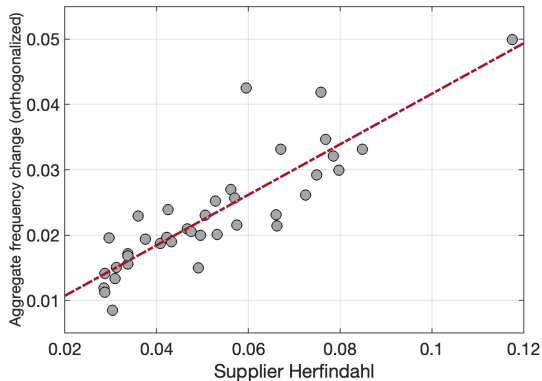
Sectoral TFP shocks

Aggregate frequency responses to sectoral TFP shocks (-20%)

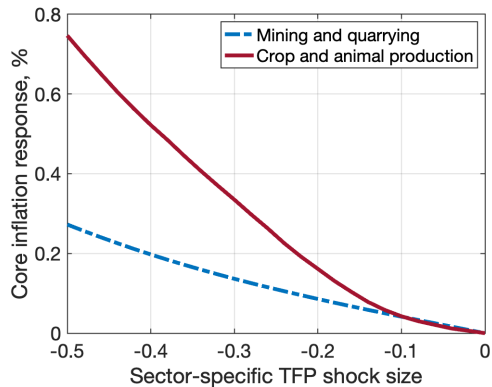


Aggregate frequency responses vs. sectoral Supplier Centrality

(a) Aggregate adjustment frequency



(b) Core inflation response

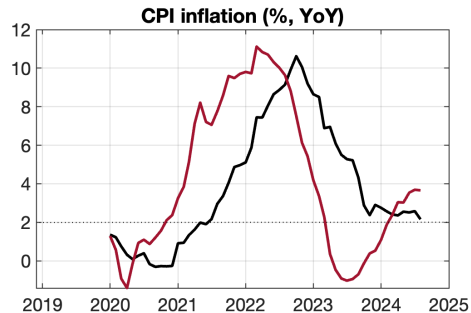
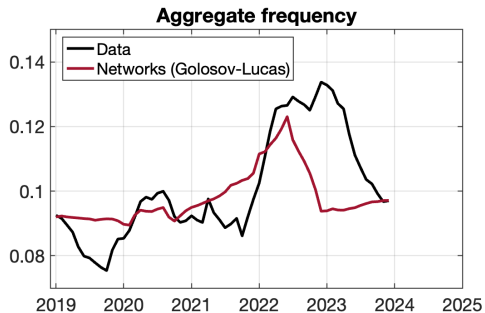


APPLICATION: (POST-) COVID EURO AREA INFLATION

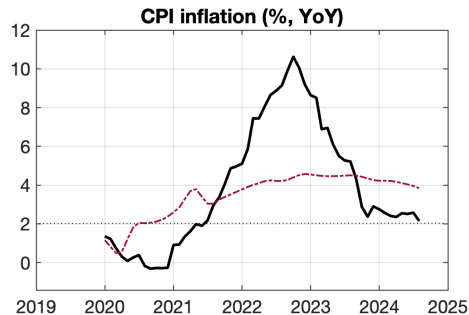
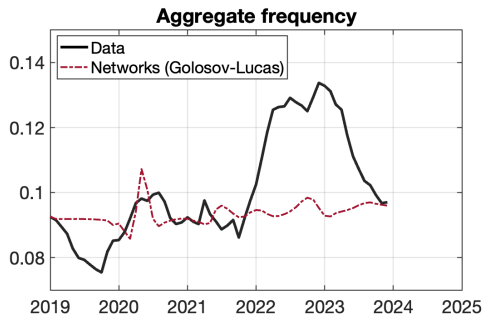
Model vs. Data

- To assess the model quantitatively, we feed in observed demand and supply processes as exogenous shocks
- **Aggregate demand shock:** Euro Area nominal GDP as a proxy for the $\{M_t\}_{t \geq 0}$ process
- **Energy price shock:** calibrate the productivity process of the "Mining and Quarrying" sector to match the IMF Global Price of Energy Index movements
- **Food price shock:** calibrate the productivity process of the "Crop and Animal Production" sector to match the IMF Global Price of Food Index movements
- **Labor market shock:** calibrate the productivity process of the labor union sector to match the hourly earnings dynamics in the Euro Area

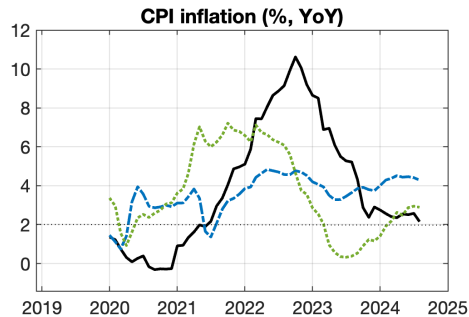
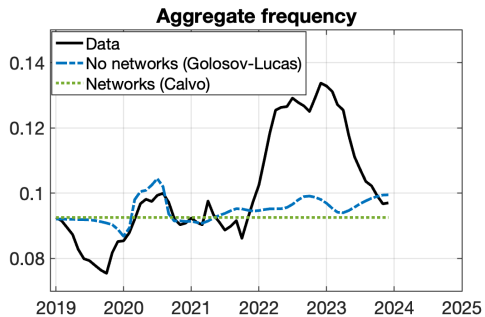
Model vs. Data: baseline setup, all shocks



Model vs. Data: baseline setup, no commodity shocks



Model vs. Data: alternative setups, all shocks



Conclusions

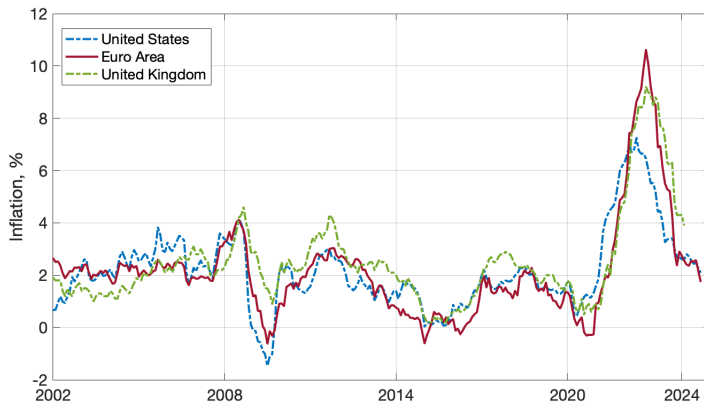
- Present a **dynamic quantitative** general equilibrium model that features: a number of **sectors interconnected by networks** with **state-dependent pricing** that is solved **fully non-linearly**
- Networks **slow down** the extensive margin pricing response to **demand shocks**: **cascades dampening**
- Networks **speed up** the extensive margin response to **supply shocks**: **cascades amplification**
- **Interaction** of networks and pricing cascades crucial for **quantitatively** matching the observed surges in inflation and repricing frequency in the Euro Area

References

- Gautier, Erwan, Cristina Conflitti, Riemer P. Faber, Brian Fabo, Ludmila Fadejeva, Valentin Jouvanceau, Jan-Oliver Menz, Teresa Messner, Pavlos Petroulas, Pau Roldan-Blanco, Fabio Rumler, Sergio Santoro, Elisabeth Wieland, and Hélène Zimmer (2024) “New Facts on Consumer Price Rigidity in the Euro Area,” *American Economic Journal: Macroeconomics*, Vol. 16, p. 386–431.
- Golosov, Mikhail and Robert E. Lucas (2007) “Menu Costs and Phillips Curves,” *Journal of Political Economy*, Vol. 115, pp. 171–199.

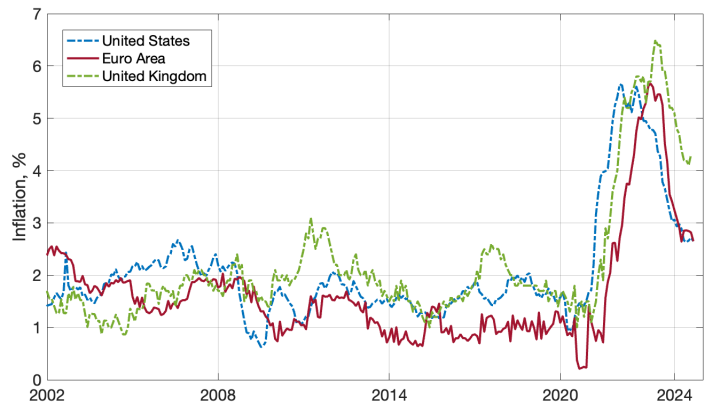
APPENDIX

Evidence I: inflation spikes in advanced economies (headline)



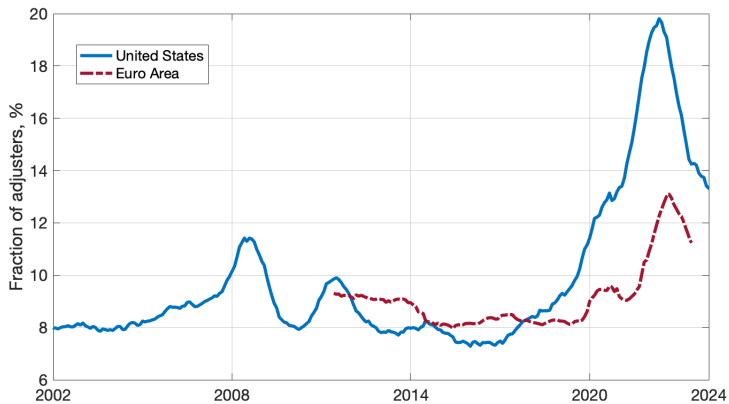
Source: FRED.

Evidence I: inflation spikes in advanced economies (core)



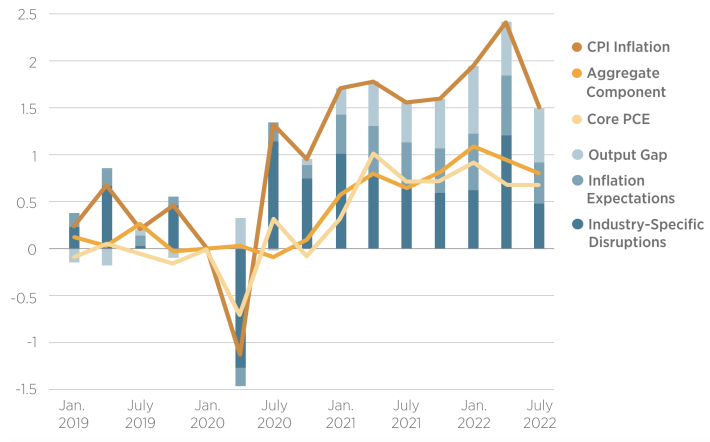
Source: FRED.

Evidence II: changes in frequency of price adjustment



Source: Montag and Villar (2024), Dedola et al. (2024).

Evidence III: sectoral origins of inflation



Source: Rubbo (2024).

Cascades dampening under monetary shocks

Proposition

Let ϱ_i be the probability that a firm in sector i decides to adjust its price. Following a monetary shock m , denote by $\Delta \varrho_i(m)$ the change relative to steady-state, then:

$$\frac{1}{\chi_i} \Delta \varrho_i(m) \approx \left[m + \bar{\mu} \times \mathcal{C}_i + N \times \text{Cov} \left((\bar{\Psi} - I)^{(i)}, \boldsymbol{\mu} \right) \right]^2$$

where $\chi_i \equiv -\Xi_i'' \left(\sqrt{\frac{2\kappa_i}{\epsilon-1}} \right) > 0$ and Ξ_i is CDF of $\mathcal{N}(0, \sigma_i^2)$, $\mathcal{M}_i$ is the sectoral markup and $\bar{\mu} \equiv \frac{1}{N} \sum_{i=1}^N \log \mathcal{M}_i$, $\boldsymbol{\mu} \equiv [\log \mathcal{M}_1, \dots, \log \mathcal{M}_N]^T$, $\bar{\Psi} \equiv (I - \bar{\Omega})^{-1}$ is the Leontief inverse matrix, and

$$\mathcal{C}_i \equiv \sum_{j=1}^N \bar{\Psi}_{i,j} - 1$$

is the **customer centrality** of sector i .

Cascades amplification under aggregate TFP shocks

Proposition

Let ϱ_i be the probability that a firm in sector i decides to adjust its price. Following a combination of sectoral productivity shocks $\mathbf{a} \equiv \{a_j\}_{j=1}^N$, denote by $\Delta\varrho_i(\mathbf{a})$ the change relative to steady-state, then:

$$\frac{1}{\chi_i} \Delta\varrho_i(\mathbf{a}) \approx \left[\sum_{j=1}^N \bar{\Psi}_{ij} a_j - \bar{\mu} \times \mathcal{C}_i - N \times \text{Cov} \left((\bar{\Psi} - I)^{(i)}, \boldsymbol{\mu} \right) \right]^2$$

where $\chi_i \equiv -\Xi_i'' \left(\sqrt{\frac{2\bar{\kappa}_i}{\epsilon-1}} \right) > 0$ and Ξ_i is CDF of $\mathcal{N}(0, \sigma_i^2)$, $\mathcal{M}_i$ is the sectoral markup and $\bar{\mu} \equiv \frac{1}{N} \sum_{i=1}^N \log \mathcal{M}_i$, $\boldsymbol{\mu} \equiv [\log \mathcal{M}_1, \dots, \log \mathcal{M}_N]^T$, $\bar{\Psi} \equiv (I - \bar{\Omega})^{-1}$ is the Leontief inverse matrix, and $\mathcal{C}_i$ is the customer centrality measure introduced in (4).

A notable special case is that of an aggregate TFP shock $a_j = a, \forall j$:

$$\frac{1}{\chi_i} \Delta\varrho_i(a) \approx \left[a + (a - \bar{\mu}) \times \mathcal{C}_i - N \times \text{Cov} \left((\bar{\Psi} - I)^{(i)}, \boldsymbol{\mu} \right) \right]^2.$$

Cascades amplification under sectoral TFP shocks

Proposition

Set $\bar{\kappa}_i = \bar{\kappa}$, $\sigma_i = \sigma$, $\forall i$ and assume $\text{Cov}(\bar{\Psi}_{(i)}, \mathcal{C}) = 0, \forall i$. Let $\varrho \equiv \frac{1}{N} \sum_{i=1}^N \varrho_i$ be the average probability of adjustment. Following a TFP shock specific to sector k , a_k , denote by $\Delta \varrho(a_k)$ the change in the average adjustment probability relative to its steady-state value and assume that $\text{Cov}\left((\bar{\Psi} - I)^{(i)}, \mu\right) = 0, \forall i$, then:

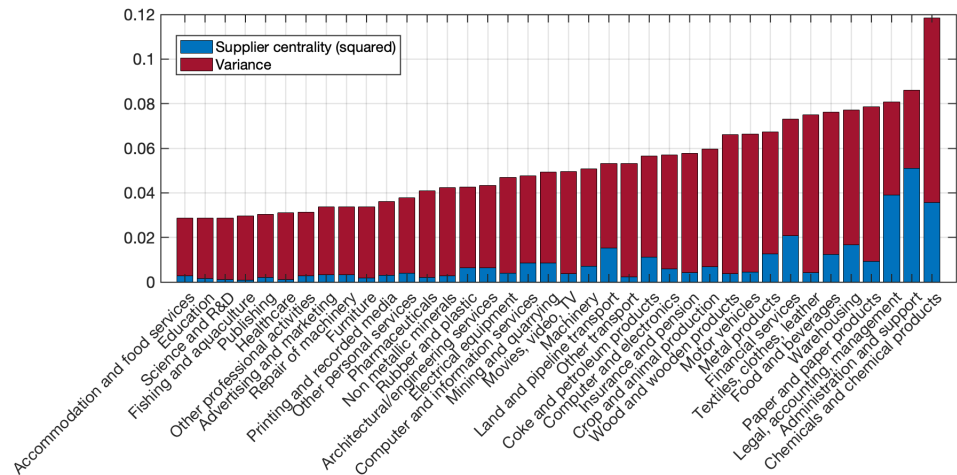
$$\frac{1}{\chi} \Delta \varrho(a_k) \approx \mathcal{H}_k \times a_k^2 - 2\bar{\mu} \times \bar{\mathcal{C}} \times \mathcal{S}_k \times a_k + \bar{\mu}^2 \bar{\mathcal{C}}^2$$

where $\chi \equiv -\Xi''\left(\sqrt{\frac{2\bar{\kappa}}{\epsilon-1}}\right) > 0$ and Ξ is CDF of $\mathcal{N}(0, \sigma^2)$, $\mathcal{M}_i$ is the sectoral markup and $\bar{\mu} \equiv \frac{1}{N} \sum_{i=1}^N \log \mathcal{M}_i$, $\mu \equiv [\log \mathcal{M}_1, \dots, \log \mathcal{M}_N]^T$, $\mathcal{C}_i$ is the customer centrality introduced in (4) and $\bar{\mathcal{C}} \equiv \frac{1}{N} \sum_{i=1}^N \mathcal{C}_i$, $\bar{\mathcal{C}}^2 \equiv \frac{1}{N} \sum_{i=1}^N \mathcal{C}_i^2$, $\mathcal{C} \equiv [\mathcal{C}_1, \dots, \mathcal{C}_N]^T$, and

$$\mathcal{H}_k \equiv \frac{1}{N} \sum_{i=1}^N \bar{\Psi}_{i,k}^2, \quad \mathcal{S}_k \equiv \frac{1}{N} \sum_{i=1}^N \bar{\Psi}_{i,k}$$

are, respectively, the **supplier Herfindahl** ($\mathcal{H}_k$) and **supplier centrality** ($\mathcal{S}_k$) of sector k .

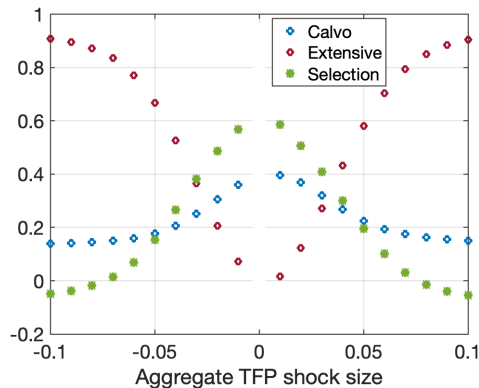
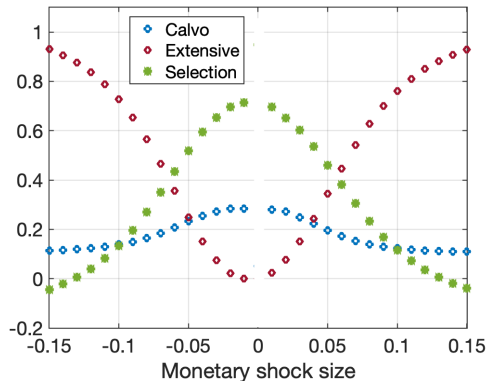
Supplier Herfindahl: a decomposition



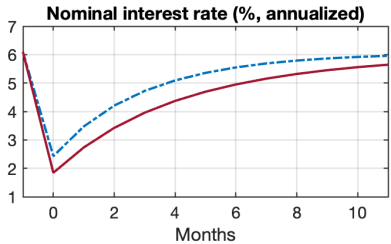
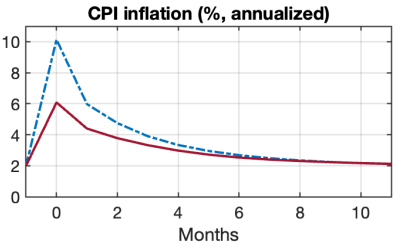
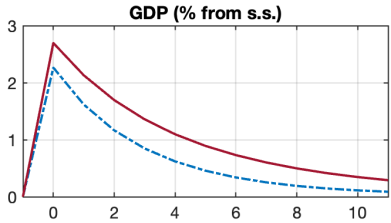
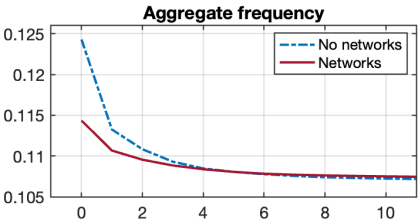
Inflation decomposition and network effects

- Make use of the following inflation decomposition:

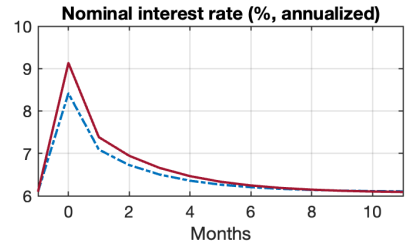
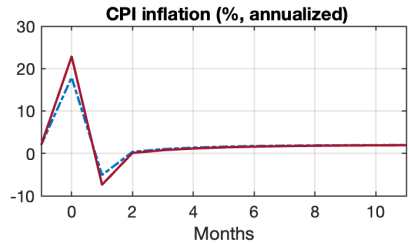
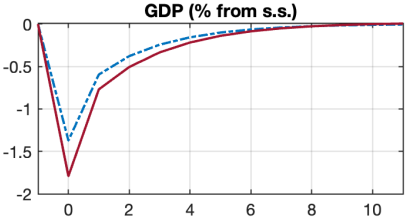
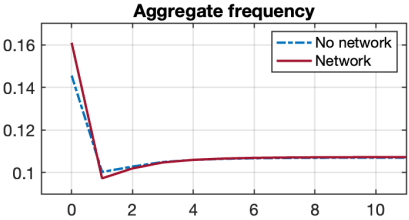
$$\Delta\pi = \Delta\pi^{\text{Calvo}} + \Delta\pi^{\text{Extensive}} + \Delta\pi^{\text{Selection}}$$



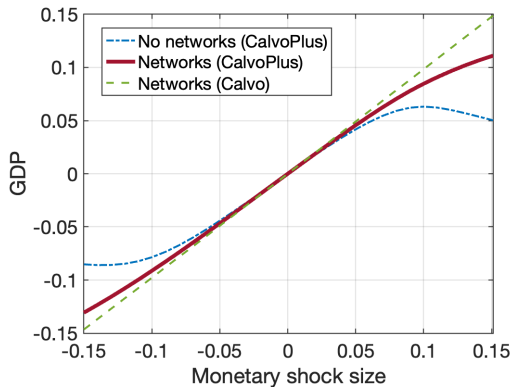
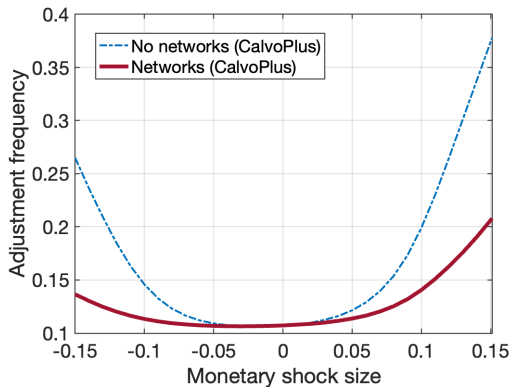
Cascades dampening following monetary shocks: Taylor rule



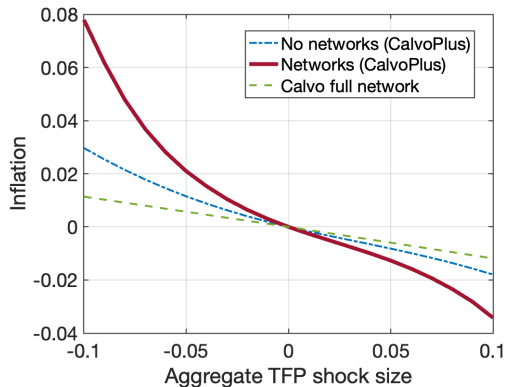
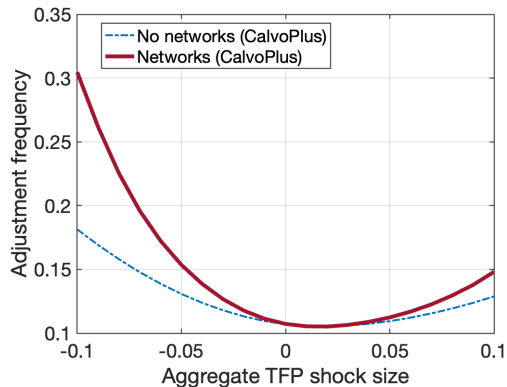
Cascades amplification following TFP shocks: Taylor rule



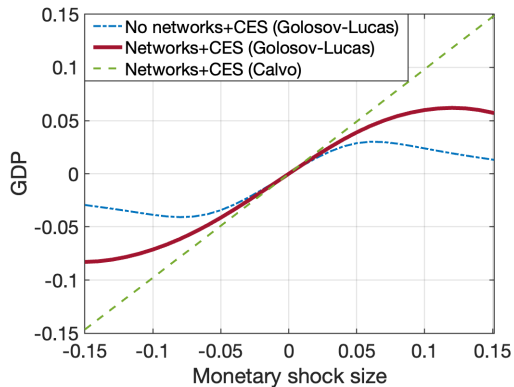
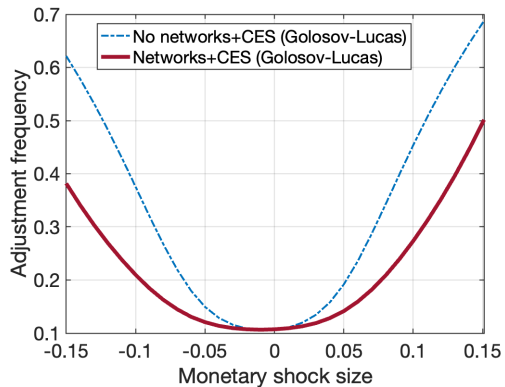
Cascades dampening following monetary shocks: CalvoPlus



Cascades amplification following TFP shocks: CalvoPlus



Cascades dampening following monetary shocks: CES aggregation



Cascades amplification following TFP shocks: CES aggregation

