Business Cycles with Pricing Cascades

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Inflation: Drivers and Dynamics

European Central Bank, Frankfurt

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- 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**

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     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**

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  - 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

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- **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

Households

- The representative household maximizes expected lifetime utility:

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

  subject to a standard budget constraint

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

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

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

  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:

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

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 $\quad \overline{\alpha}_i + \sum_{k=1}^{N} \overline{\omega}_{ik} = 1, \quad \overline{\alpha}_i \geq 0, \overline{\omega}_{ik} \geq 0, \ \forall i, k$

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- Cost-minimization delivers the following marginal cost:

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

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

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- 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

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

$$V_{i,t}(p) = \tilde{\mathcal{D}}_{i,t}(p) + \beta \mathbb{E}_t \left[\{1 - \eta_{i,t+1}(p - \sigma_i \varepsilon_{i,t+1} - m_{t+1})\} \times V_{i,t+1}(\overbrace{p - \sigma_i \varepsilon_{i,t+1} - m_{t+1}}^{\text{"Eroded" real price}}) \right]$$

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

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

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

STATIC SETUP

Intuition in a simplified setup

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- For a firm j in sector i, the real profit gain from price adjustment satisfies:

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

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

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

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

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

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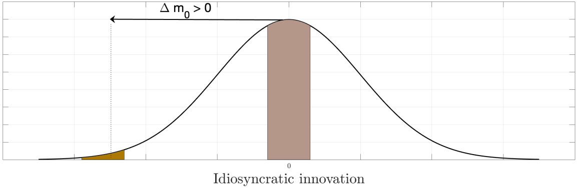

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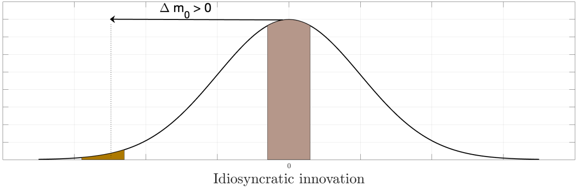

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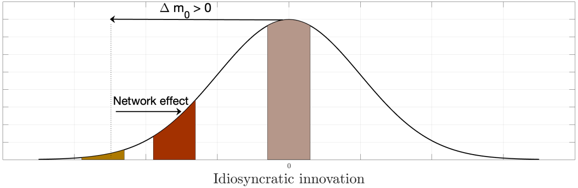

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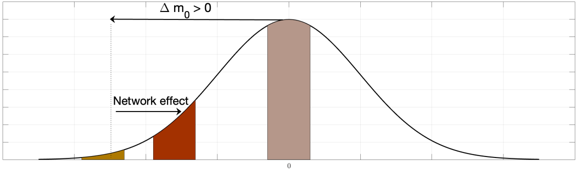

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Proposition (Cascades dampening: monetary shocks)

For a monetary shock $\boldsymbol{m}$*, 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*** $\mathcal{C}_i$

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

TFP shock: **cascades amplification** by networks

- **Inaction region**: a firm will **not** adjust if it draws an innovation in $(\kappa_{i,t} = \overline{\kappa}_i [\tilde{P}_{i,t} / \tilde{P}^*_{i,t}]^{\epsilon-1} \lambda_{i,t})$

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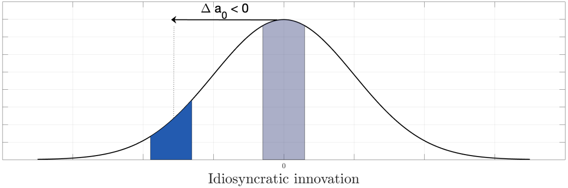

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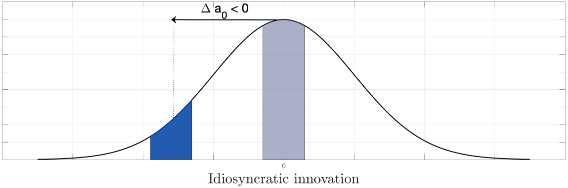

- **Inflationary TFP deterioration**: $\log \tilde{P}_k > 0, \forall k$

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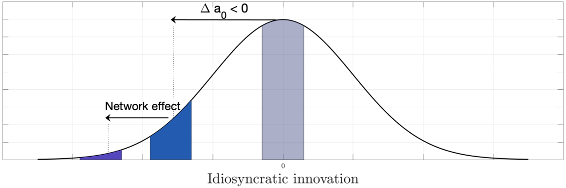

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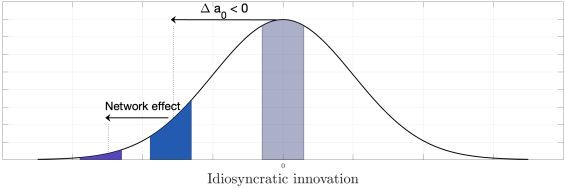

- **Inflationary TFP deterioration**: $\log \tilde{P}_k > 0, \forall k$

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*** $\mathcal{C}_i$

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

TFP shock: **cascades amplification** by networks

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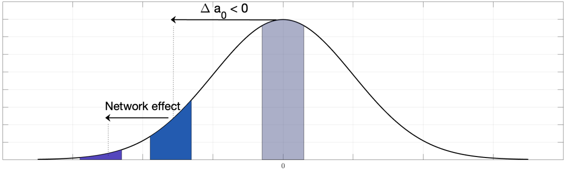


- **Inflationary TFP deterioration**: $\quad \log \tilde{P}_k > 0, \forall k$

Proposition (Cascades amplification: sectoral TFP shock)

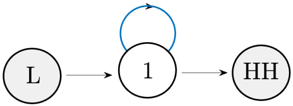
For a sectoral TFP shock $\mathbf{a_i}$, under counter-moving sectoral prices, average probab. of adjustment around symmetric s.s. is:

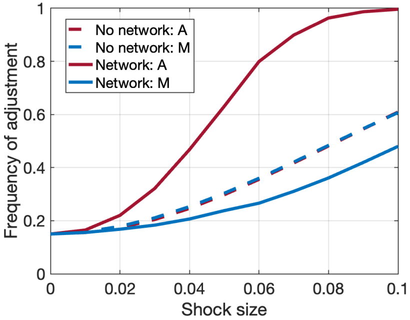
$$\overline{\varrho}(\mathbf{a_i}) \quad \underset{\sim}{\propto} \quad \mathcal{H}_i$$

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

Toy example 1: roundabout production

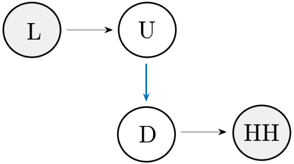
- Marginal cost: $MC(j) = \zeta(j) \times \frac{1}{A} \times M^{\overline{\alpha}} P^{1-\overline{\alpha}}$

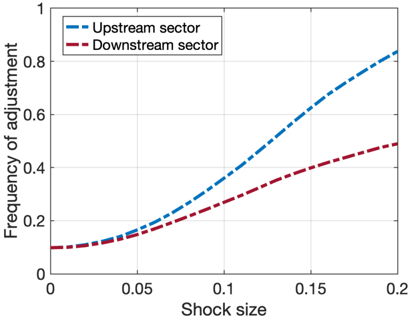




Toy example 2: two-sector vertical chain

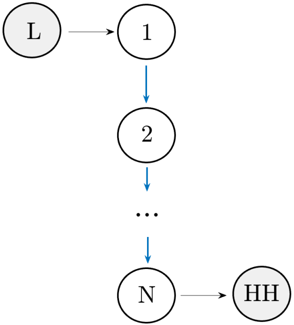
- Marginal costs: $MC_U(j) = \zeta_U(j) \times \frac{1}{A_U} \times M, \quad MC_D(j) = \zeta_D(j) \times \frac{1}{A_D} \times P_U$

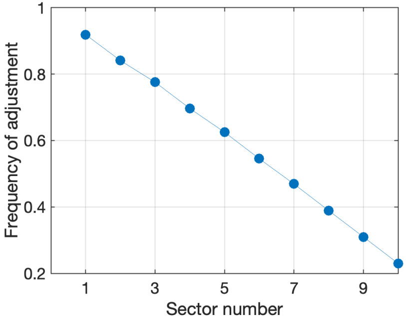




Toy example 3: *N*-sector vertical chain

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





QUANTITATIVE RESULTS

Calibration (Euro Area, monthly frequency)

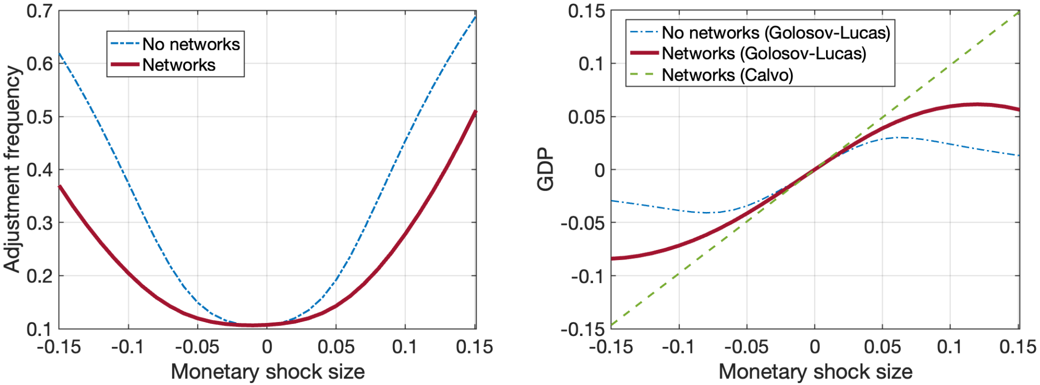
		Aggregate parameters	
β	$0.96^{1/12}$	Discount factor (monthly)	Golosov and Lucas (2007)
ϵ	3	Goods elasticity of substitution	Midrigan (2011)
$\overline{\pi}$	0.02/12	Trend inflation (monthly)	ECB target
ρ	0.90	Persistence of the TFP shock	Half-life of seven months
		Sectoral parameters	
N	39	Number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

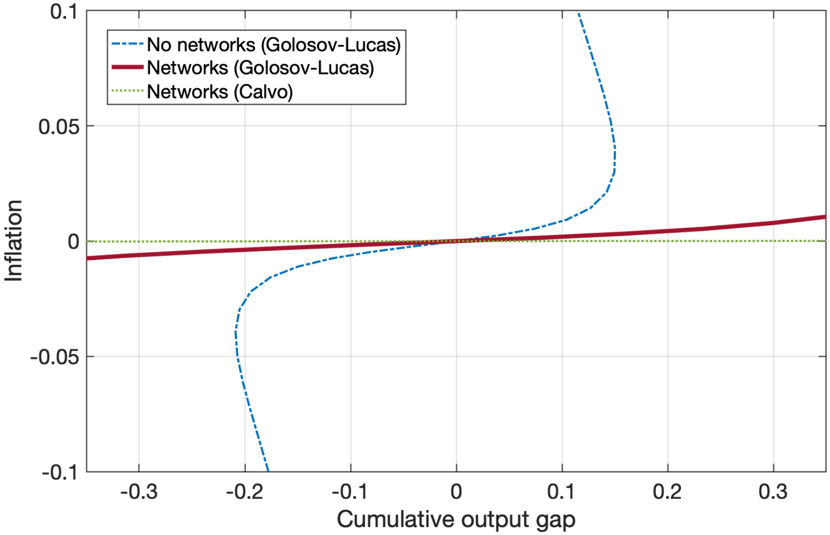
$$\log M_t = \overline{\pi} + \log M_{t-1} + \varepsilon_t^M$$

Cascades dampening following monetary shocks

(a) Aggregate adjustment frequency (b) GDP



Non-linear **Phillips Curves**

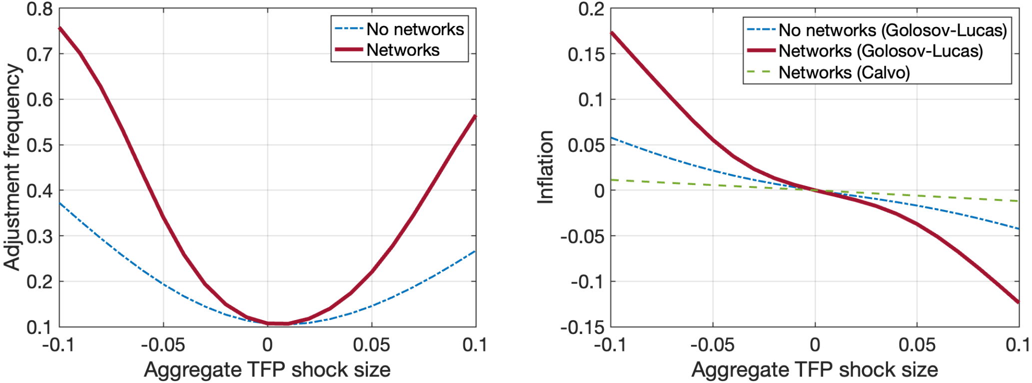


Aggregate TFP shocks

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

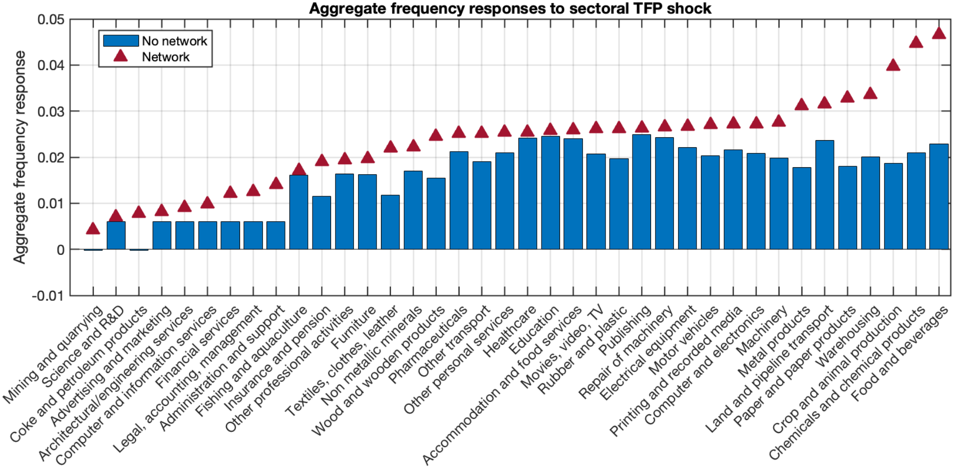
Cascades amplification following TFP shocks

(a) Aggregate adjustment frequency (b) CPI inflation



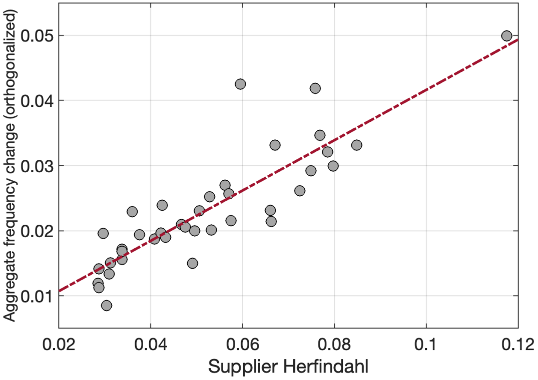
Sectoral TFP shocks

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

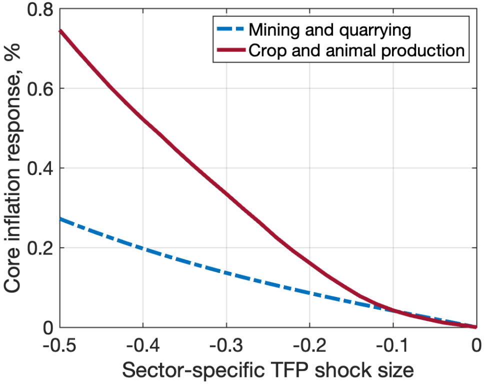


Aggregate frequency responses vs. sectoral **Supplier Centrality**

(a) Aggregate adjustment frequency



(b) Core inflation response

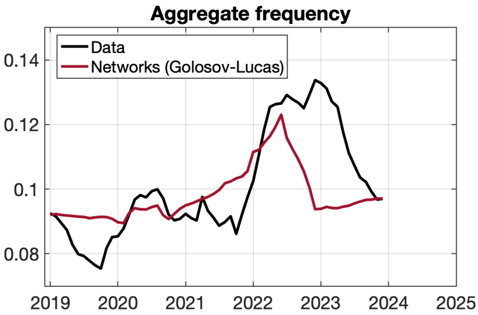


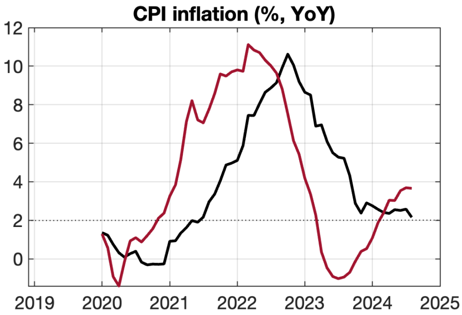
APPLICATION: (POST-) COVID EURO AREA INFLATION

Model vs. Data

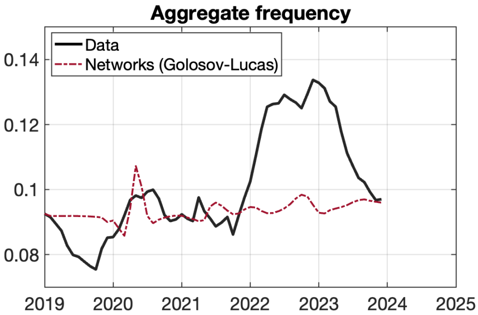
- To assess the model quantitatively, we feed in observed demand and supply processes as exogenous shocks
- **Aggregate demand shock**: Euro Area nominal GDP as a proxy for the $\{M_t\}_{t\geq 0}$ process
- **Energy price shock**: calibrate the productivity process of the "Mining and Quarrying" sector 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

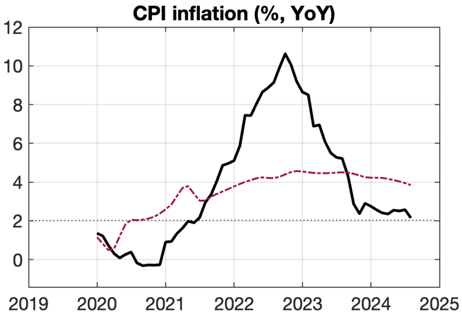
Model vs. Data: baseline setup, all shocks



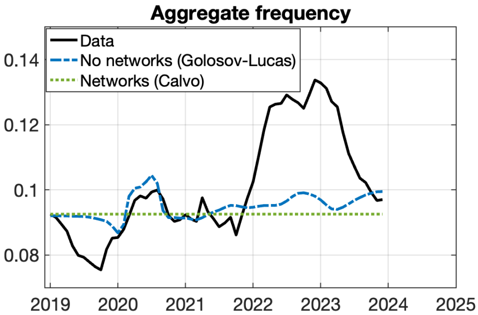


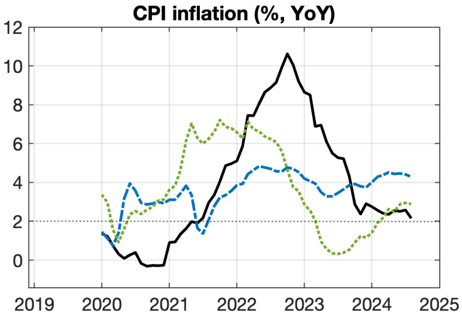
Model vs. Data: baseline setup, no commodity shocks





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

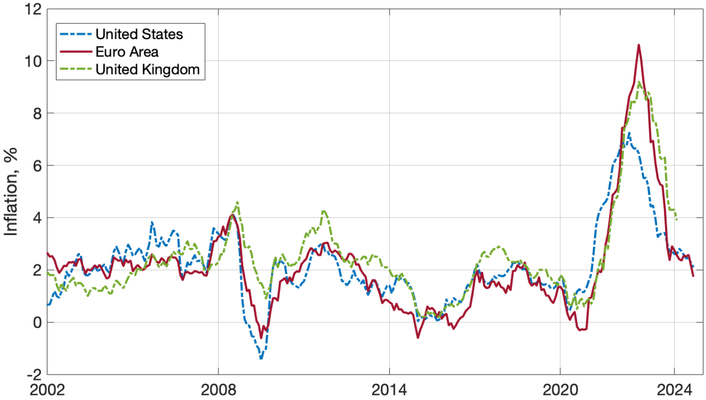
References

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

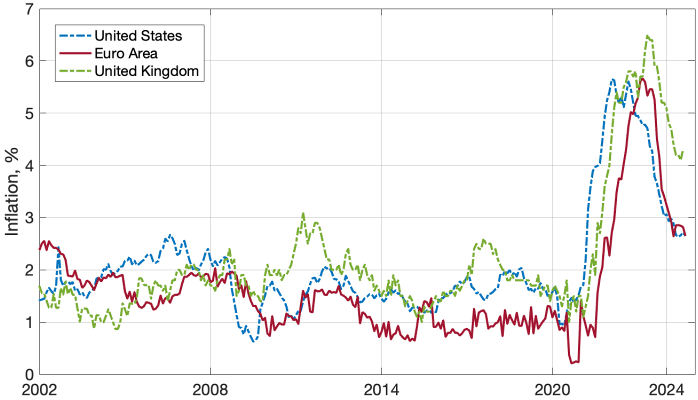
Evidence I: inflation spikes in advanced economies (headline)



Source: FRED.

Back

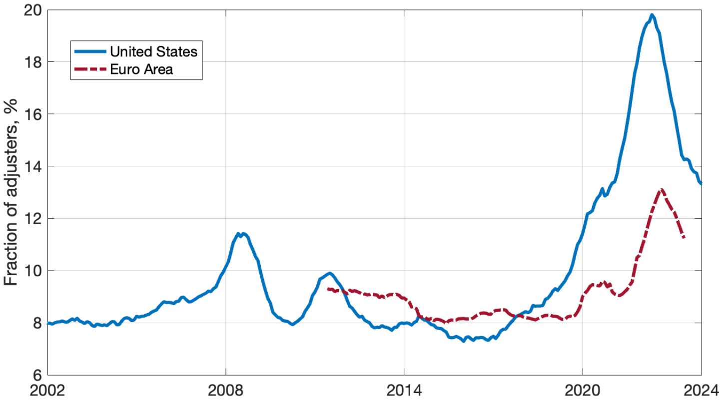
Evidence I: inflation spikes in advanced economies (core)



Source: FRED.

Back

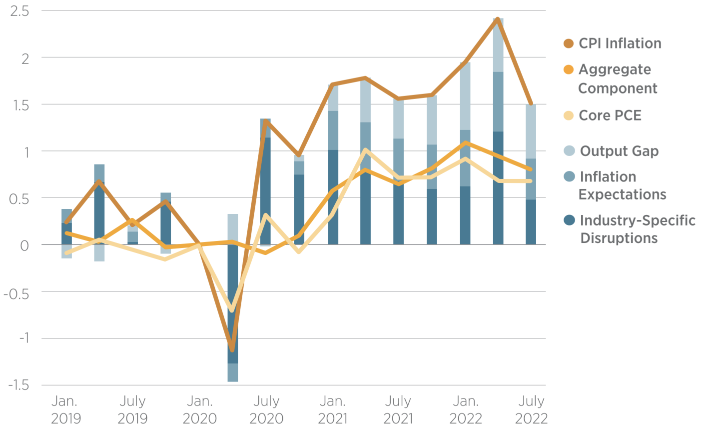
Evidence II: changes in frequency of price adjustment



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

Back

Evidence III: sectoral origins of inflation



Source: Rubbo (2024).

▸ Back

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:

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

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* $\overline{\mu} \equiv \frac{1}{N}\sum_{i=1}^{N} \log \mathcal{M}_i$, $\boldsymbol{\mu} \equiv [\log \mathcal{M}_1, ..., \log \mathcal{M}_N]^T$, $\overline{\Psi} \equiv (I - \overline{\Omega})^{-1}$ *is the Leontief inverse matrix, and*

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

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

Back

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:

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

where $\chi_i \equiv -\Xi_i''\left(\sqrt{\frac{2\overline{\kappa}_i}{\epsilon-1}}\right) > 0$ *and* Ξ_i *is CDF of* $\mathcal{N}(0, \sigma_i^2)$, $\mathcal{M}_i$ *is the sectoral markup and* $\overline{\mu} \equiv \frac{1}{N}\sum_{i=1}^N \log \mathcal{M}_i$, $\boldsymbol{\mu} \equiv [\log \mathcal{M}_1, ..., \log \mathcal{M}_N]^T$, $\overline{\Psi} \equiv (I - \overline{\Omega})^{-1}$ *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 $a_j = a, \forall j$:

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

Back

Cascades amplification under sectoral TFP shocks

Proposition

Set $\overline{\kappa}_i = \overline{\kappa}, \sigma_i = \sigma, \forall i$ and assume $Cov(\overline{\Psi}_{(i)}, \boldsymbol{\mathcal{C}}) = 0, \forall i$. 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 $Cov\left((\overline{\Psi} - I)^{(i)}, \boldsymbol{\mu}\right) = 0, \forall i$, then:

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

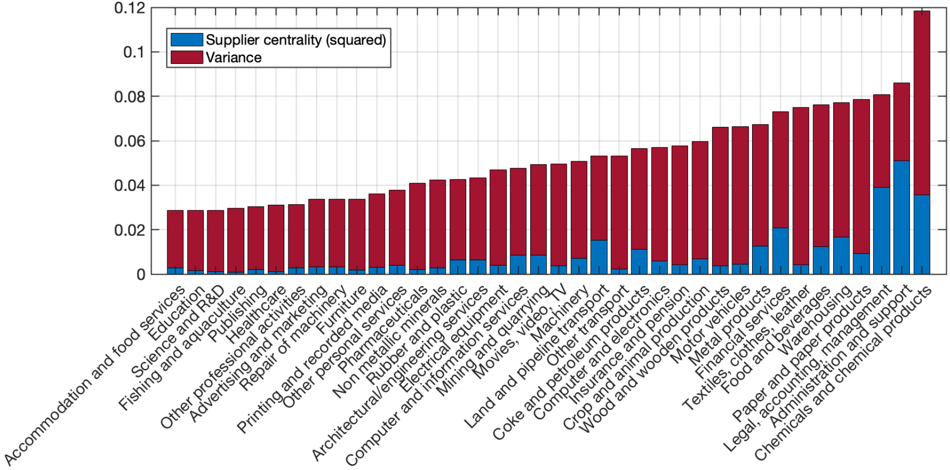
where $\chi \equiv -\Xi''\left(\sqrt{\frac{2\overline{\kappa}}{\epsilon-1}}\right) > 0$ and Ξ is CDF of $\mathcal{N}(0, \sigma^2)$, $\mathcal{M}_i$ is the sectoral markup and $\overline{\mu} \equiv \frac{1}{N}\sum_{i=1}^{N} \log \mathcal{M}_i$, $\boldsymbol{\mu} \equiv [\log \mathcal{M}_1, ..., \log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

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

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

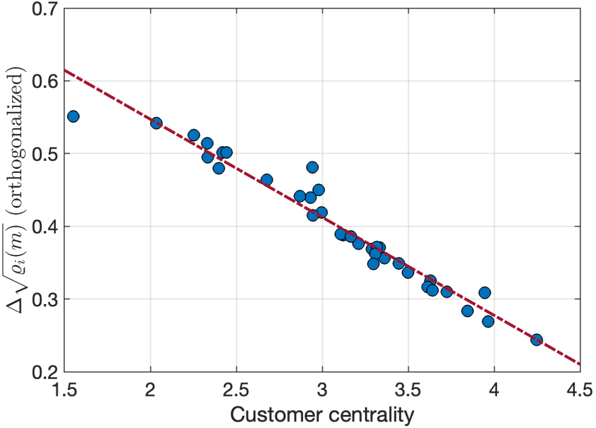
Back

Supplier Herfindahl: a decomposition

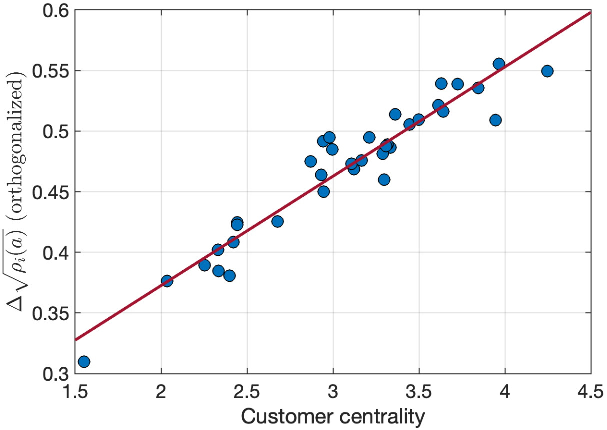


▸ Back

Sectoral frequency responses vs. Customer Centrality



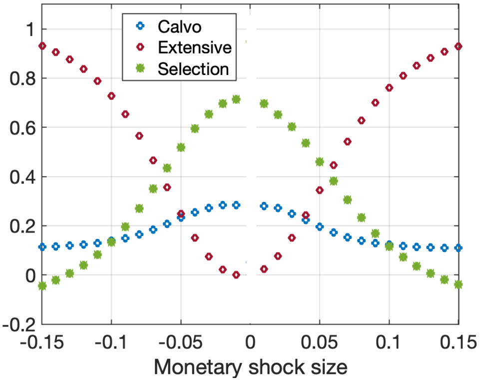
Sectoral frequency responses vs. Customer Centrality

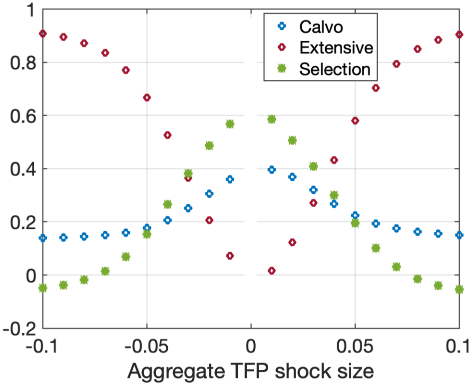


Inflation decomposition and network effects

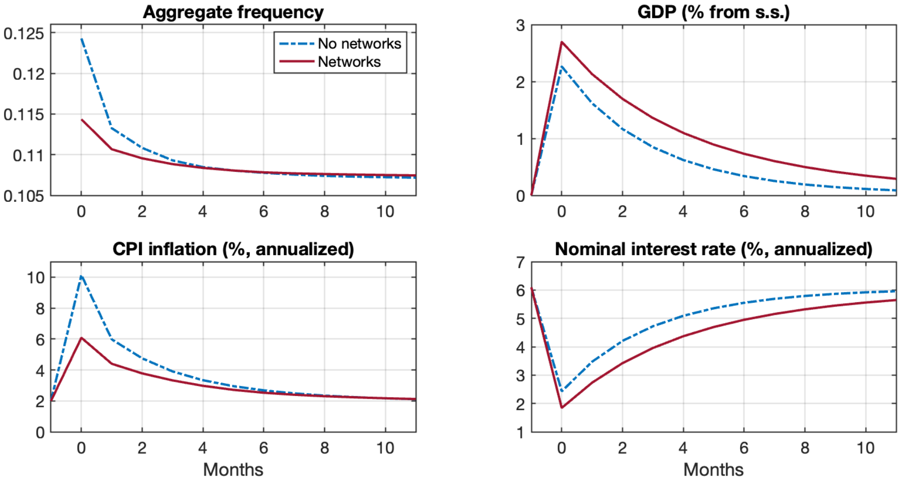
- Make use of the following inflation decomposition:

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

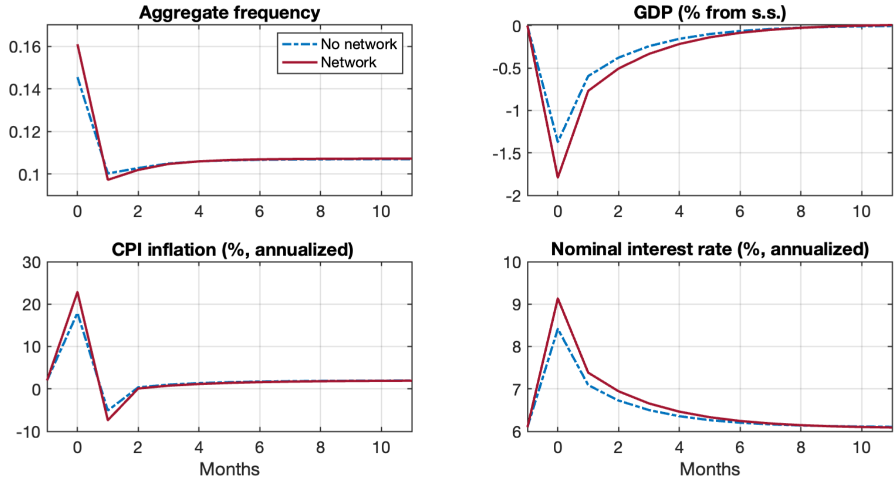




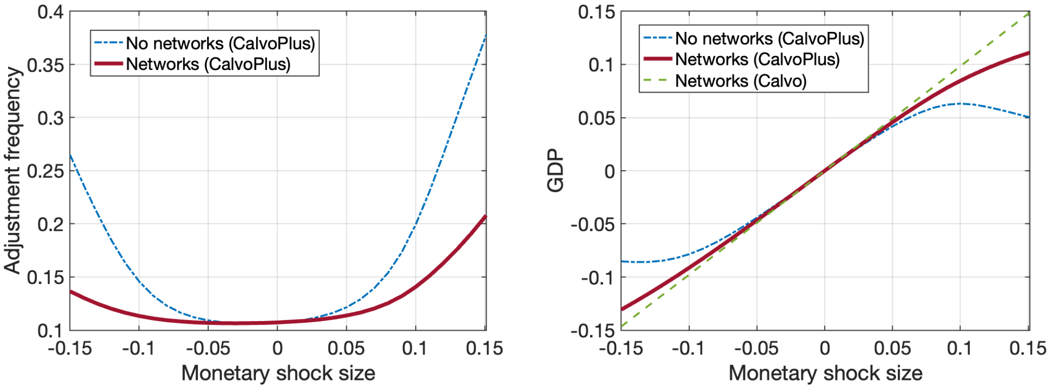
Cascades dampening following monetary shocks: Taylor rule



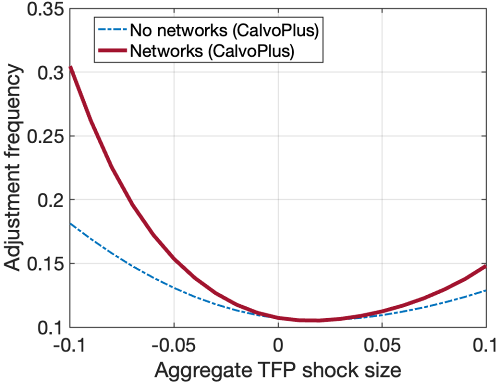
Cascades amplification following TFP shocks: Taylor rule

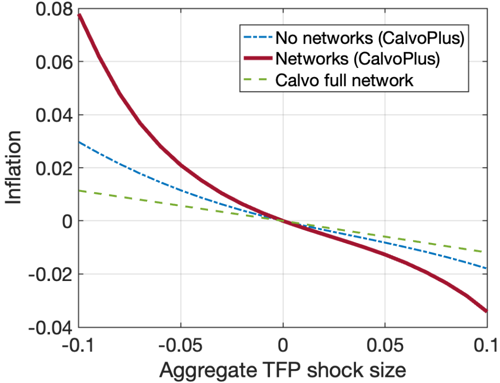


Cascades dampening following monetary shocks: CalvoPlus

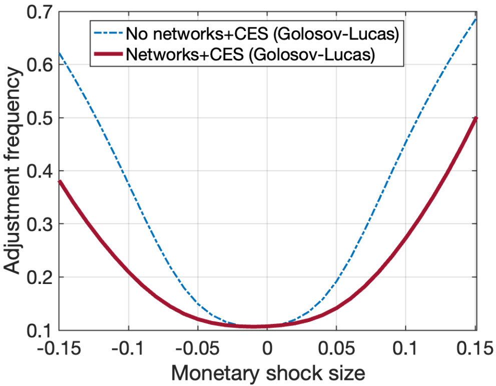


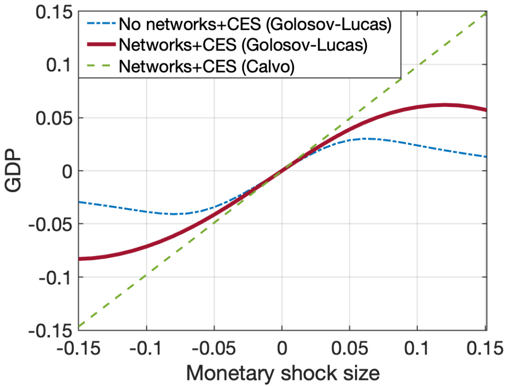
Cascades amplification following TFP shocks: CalvoPlus





Cascades dampening following monetary shocks: CES aggregation





Cascades amplification following TFP shocks: CES aggregation