Large Shocks, Networks and State-Dependent Pricing

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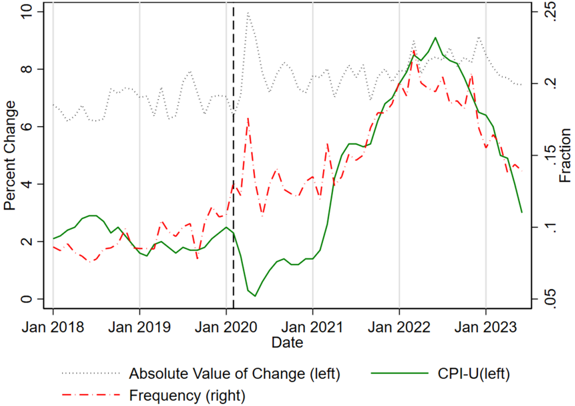
Motivation

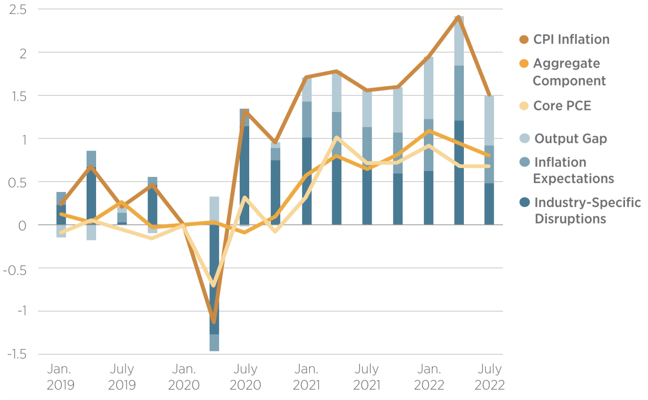
- The New Keynesian framework has had a great influence on both academic macroeconomics as well as the practical conduct of monetary policy (Woodford, 2010; Galí, 2015)
- Recent inflationary episodes have brought both renewed interest and new evidence regarding the drivers and dynamics of price setting and inflation:

Evidence: changes in frequency of price adjustemnt



Source: Montag and Villar (2023).

Evidence: sectoral origins of inflation



Source: Rubbo (2024).

Motivation

- The New Keynesian framework has had a great influence on both academic macroeconomics as well as the practical conduct of monetary policy (Woodford, 2010; Galí, 2015)

- Recent inflationary episodes have brought both renewed interest and new evidence regarding the drivers and dynamics of price setting and inflation:

  i Cyclical fluctuations in the **frequency of price adjustment**

  ii Importance of **sector-specific** drivers of inflation

  iii Possibility of **large swings** in inflation

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

Key results

- **Monetary shocks** Networks **dampen** the response of the extensive margin: **anti-cascades** in pricing

  i Networks dampen the effect of monetary shocks on the marginal cost, thus compressing movements in the optimal reset price (less likely to be pushed out of Ss bands)

  ii Quantitatively, expands the maximum possible monetary stimulus of GDP ($2.5\% \rightarrow 5\%$)

- **TFP shocks** (Agg./sectoral) Networks **amplify** the response of the extensive margin: **cascades** in pricing

  i Networks amplify the effect of TFP shocks on the marginal cost, thus enhancing movements in the optimal reset price (more likely to be pushed out of Ss bands)

  ii Quantitatively, creates inflationary spirals following aggregate TFP shocks, or TFP shocks to sectors that are major suppliers to the rest of the economy

MODEL

Model overview

- **Timing**: infinite-horizon setting in discrete time, indexed by $t = 0, 1, 2, \ldots$
- **Households**: continuum of identical households, exists a representative one; consume output and supply labor
- **Firms**: continuum of monopolistically competitive firms, each belongs to one of N sectors, indexed $i \in \{1, 2, \ldots, N\}$; 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:

$$\max_{\{C_t, N_t, B_t\}_{t \geq 0}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\log C_t - \nu N_t\right]$$

subject to a standard budget constraint

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

- Aggregate consumption: $C_t = \left(\sum_{i=1}^{N} \overline{\omega}_{C,i}^{\frac{1}{\theta_c}} C_{i,t}^{\frac{\theta_c - 1}{\theta_c}} \right)^{\frac{\theta_c}{\theta_c - 1}}, \quad \theta_c > 0$

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

  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:

$$Y_{i,t}(j) = \frac{1}{\zeta_{i,t}(j)} \times A_{i,t} \times \left(\overline{\alpha}_i^{\frac{1}{\theta_i}} N_{i,t}^{\frac{\theta_i - 1}{\theta_i}}(j) + \sum_{k=1}^{N} \overline{\omega}_{ik}^{\frac{1}{\theta_i}} X_{i,k,t}^{\frac{\theta_i - 1}{\theta_i}}(j) \right)^{\frac{\theta_i}{\theta_i - 1}},$$

where $A_{i,t}$ is a **sectoral productivity** process, $N_{i,t}(j)$ is firm-level labor input, $X_{i,k,t}(j)$ is firm-level intermediate input demand for sector k's goods, $\theta_i > 0$ is elasticity of substitution across inputs

- Cost-minimization delivers the following marginal cost:

$$MC_{i,t}(j) = \zeta_{i,t}(j) \times \frac{1}{A_{i,t}} \times \left(\overline{\alpha}_i W_t^{1-\theta_i} + \sum_{k=1}^{N} \overline{\omega}_{ik} P_{k,t}^{1-\theta_i} \right)^{\frac{1}{1-\theta_i}} = \zeta_{i,t}(j) \times \mathcal{Q}_{i,t}(A_{i,t}, W_t, \boldsymbol{P}_t)$$

where $\boldsymbol{P}_t \equiv [P_{1,t}, ..., P_{N,t}]$

Firms: pricing

- Let $p_{i,t}(j) \equiv \log \tilde{P}_{i,t}(j)$ be the quality-adjusted *log* relative price
- When the price does not change in nominal terms, $p_{i,t}(j)$ evolves according to

$$p_{i,t}(j) = p_{i,t-1}(j) + \log\left(\frac{P_{i,t-1}(i)}{\zeta_{i,t}(j)M_t}\right) - \log\left(\frac{P_{i,t-1}(j)}{\zeta_{i,t-1}(j)M_{t-1}}\right)$$

$$= p_{i,t-1}(j) - \sigma_i\varepsilon_{i,t} - m_t$$

where $m_t \equiv \Delta \log M_t$

- A firm in sector i starting period t with p resets its price with probability $\eta_{i,t}(p)$
- Price resetting involves paying a sector-specific fixed menu cost κ_i measured in labor hours

Firms: value function

- The value of a firm in sector i is given by the Bellman equation:

$$V_{i,t}(p) = \tilde{\mathcal{D}}_{i,t}(p,\cdot) + \mathbb{E}_t\left[\overbrace{\{1-\eta_{i,t+1}\left(p-\sigma_i\varepsilon_{i,t+1}-m_{t+1}\right)\}}^{\text{Pr. of non-adjustment}}\Lambda_{t,t+1}V_{i,t+1}(p-\sigma_i\varepsilon_{i,t+1}-m_{t+1})\right]$$

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

- Following Golosov and Lucas (2007), we assume the following adjustment hazard

$$\eta_{i,t}(p) = \mathbf{1}(L_{i,t}(p) > 0)$$

where $\mathbf{1}(\cdot)$ is the indicator function, and

$$L_{i,t}\left(p\right) = \max_{p'} V_{i,t}\left(p'\right) - V_{i,t}(p) - \kappa_i w_t$$

is the gain from adjustment (or loss from inaction), net of the menu cost.

QUANTITATIVE RESULTS

Computation

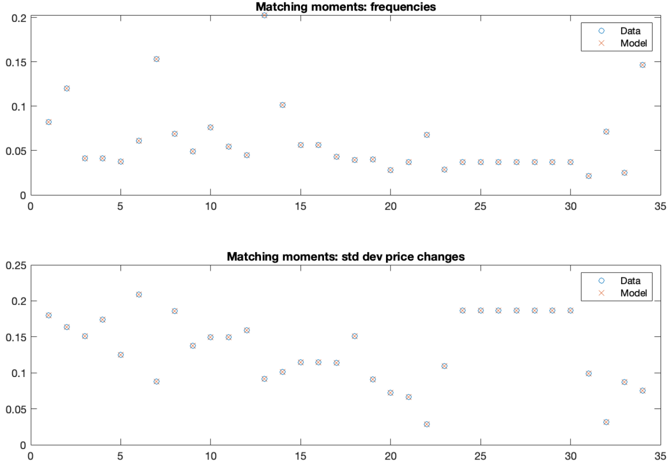
- We numerically solve for the stationary distribution of firms' prices within each sector
- Consider a sequence of money supply $\{\Delta \log M_t\}_{t=0}^{\infty}$ and productivity $\{\log A_{k,t}\}_{t=0}^{\infty}$
- Assume that after a finite time period T the economy converges back to the stationary distribution
- Starting from a guess, 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 perform aggregation:

$$\tilde{P}_{k,t}^{1-\epsilon_k} = \int_0^1 \left(\tilde{P}_{k,t}(j')\right)^{1-\epsilon_k} dj' \qquad \Delta_{k,t} = (\tilde{P}_{k,t})^{\epsilon_k} \int_0^1 \left(\tilde{P}_{k,t}(j')\right)^{-\epsilon_k} dj'.$$

Calibration (Germany, monthly frequency)

β	$0.96^{1/12}$	Discount factor (monthly)	Golosov and Lucas (2007)
ϵ	9	Goods elasticity of substitution	Galí (2015)
ν	1	Utility weight on labor	So that $w = W/M = 1$
π	0.02/12	Trend inflation (monthly)	ECB target
ρ_A	0.9	Persistence of the TFP shock	Half-life of thirteen months
ρ_μ	0	Persistence of the money growth shock	To trace out the Phillips curve
θ_c	1	Elast. of subst. across consumptions	Cobb-Douglas
θ	1	Elast. of subst. across inputs	Cobb-Douglas
N	34	Number of sectors	Data from Gautier et al. (2022)
$\boldsymbol{\omega_c}$		Sectoral consumption weights	Input-output tables for Germany
$\boldsymbol{\Omega}$		Sectoral input-output matrix	Input-output tables for Germany
$\boldsymbol{\alpha}$		Sectoral labor cost shares	German national income accounts
$\boldsymbol{\kappa}$		Sectoral menu costs	Estimated to fit frequency, std dev.
$\boldsymbol{\sigma_\zeta}$		Std. dev. of firm-level shocks	of Δp from Gautier et al. (2022)

Targeted moments: sectoral frequencies and sizes of adjustment



Impulse responses

- Consider "once and for all" MIT shocks to money supply and aggregate TFP
- For money supply, assume the following process:

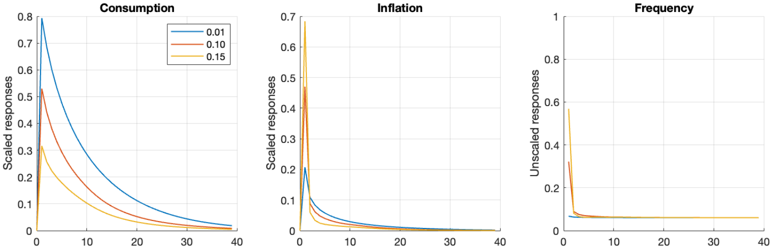
$$\log M_t = \pi + \log M_{t-1} + \varepsilon_t^M$$

- For TFP, assume an AR(1) process for each sector:

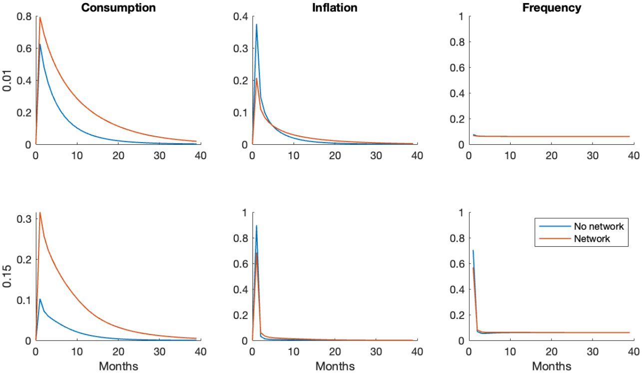
$$\log A_{k,t} = \rho_A \log A_{k,t-1} + \varepsilon_{k,t}^A$$

Monetary shocks

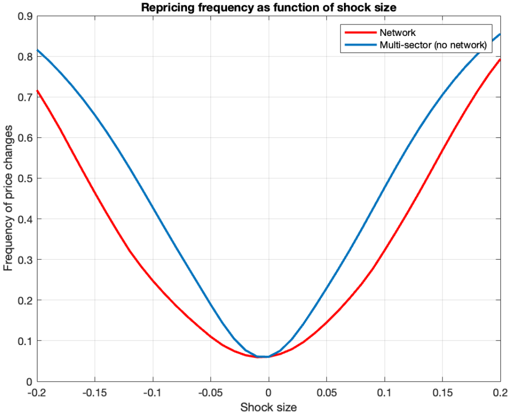
Monetary shocks of different sizes (1%, 10%, 15%)



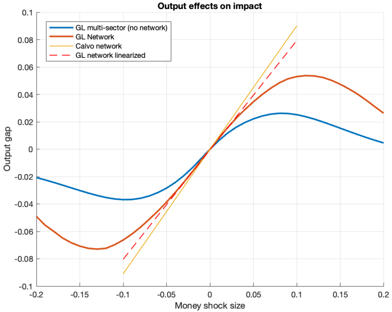
The effect of networks on size dependence

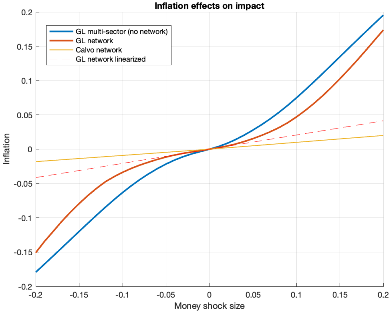


Networks slow down frequency response to monetary shocks

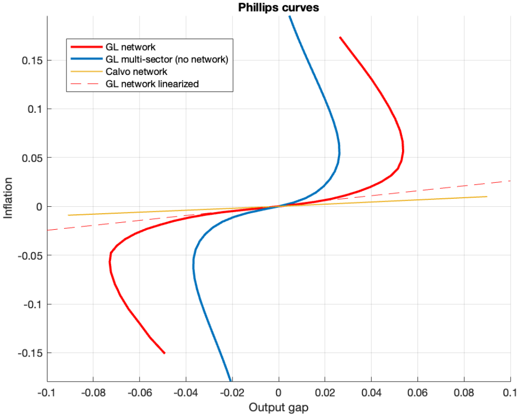


Output amplification and inflation attenuation due to network



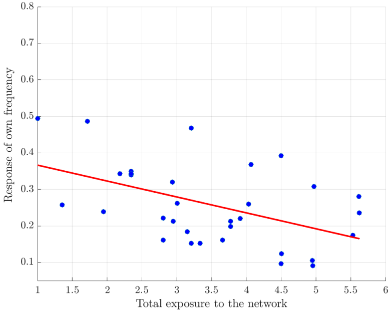


Non-linear Phillips Curve

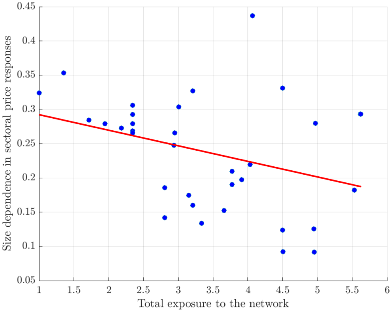


Effect of network exposure on sectoral **frequencies** and **prices**

(a) Sectoral frequencies

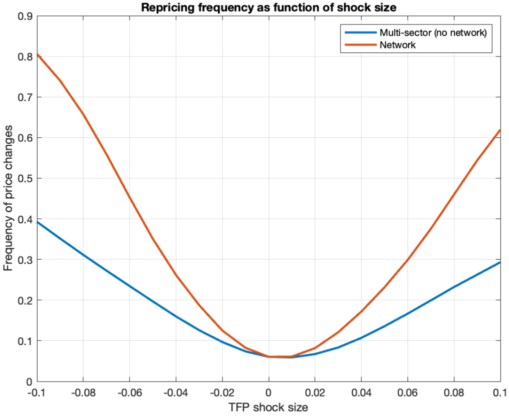


(b) Size dependence in sectoral prices

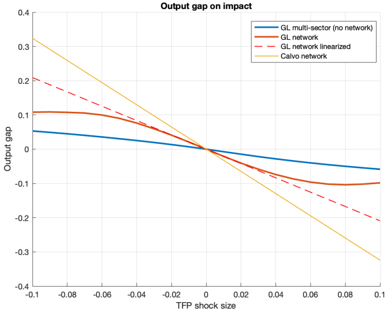


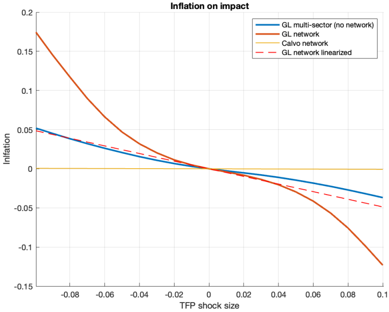
Aggregate TFP shocks

Networks speed up transmission of TFP shocks



Amplification of output gap and inflation due to network





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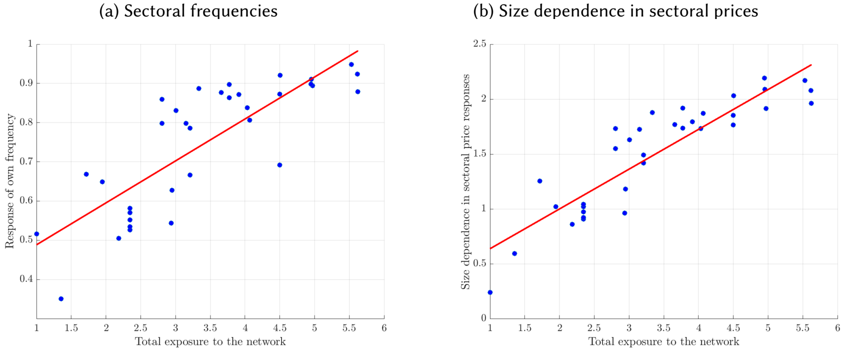
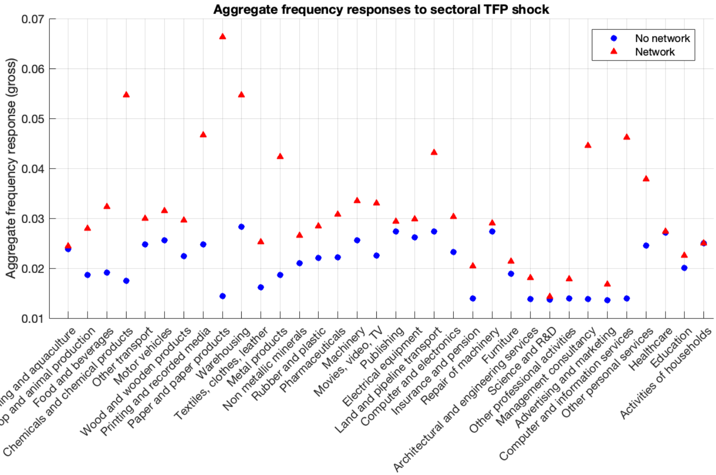
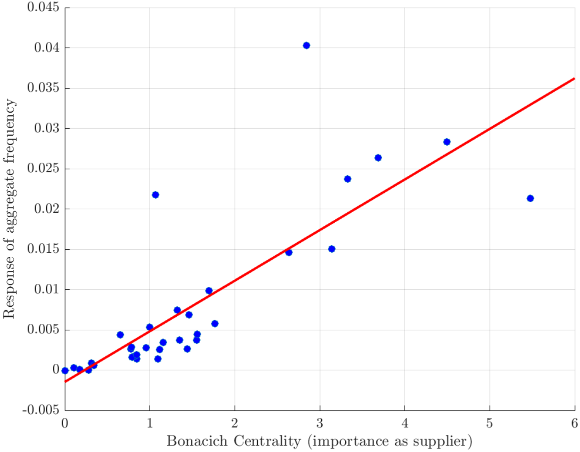


Sectoral TFP shocks

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



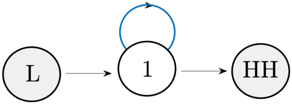
Aggregate frequency responses vs. Sectoral Centrality

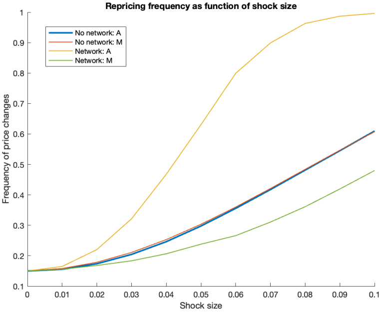


Conclusions

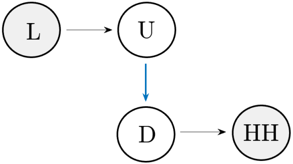
- Present a **dynamic quantitative** New Keynesian model that features: a number of sectors interconnected by networks with state-dependent pricing that is solved fully non-linearly
- Estimate the model to match sectoral pricing moments and input-output structure for Germany
- Networks **dampen** the extensive margin pricing response to **monetary shocks**
- Networks **amplify** the extensive margin response to aggregate and sectoral **TFP shocks**
- Current work
  - Calvo Plus or smooth state-dependent hazard model
  - Econometric tests of key model predictions

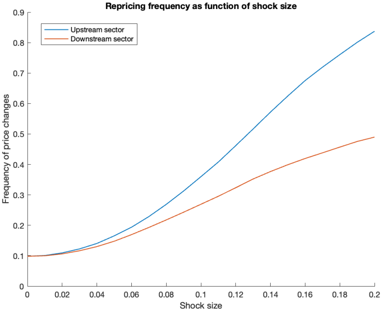
Toy example 1: roundabout production, frequency as func of shock size



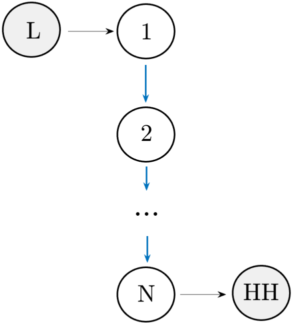


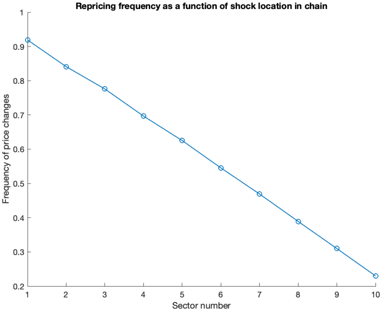
Toy example 2: production chain, frequency as func of shock size





Toy example 3: production chain, frequency as func of shock location





References

Galí, Jordi (2015) *Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework and its Applications*: Princeton Univ. Press, 2nd edition.

Gautier, Erwan, Cristina Conflitti, Riemer P Faber, Brian Fabo, Ludmila Fadejeva, Valentin Jouvanceau, Jan-Oliver Menz, Teresa Messner, Pavlos Petroulas, Pau Roldan-Blanco et al. (2022) "New facts on consumer price rigidity in the euro area," *The Quarterly Journal of Economics, forthcoming*, Vol. X, p. X.

Golosov, Mikhail and Robert E. Lucas (2007) "Menu Costs and Phillips Curves," *Journal of Political Economy*, Vol. 115, pp. 171–199.

Montag, Hugh and Daniel Villar (2023) "Price-Setting During the Covid Era," *FEDS Notes*.

Woodford, Michael (2010) "Optimal monetary stabilization policy," *Handbook of monetary economics*, Vol. 3, pp. 723–828.