The Inflation Accelerator

Andres Blanco Corina Boar Callum Jones Virgiliu Midrigan

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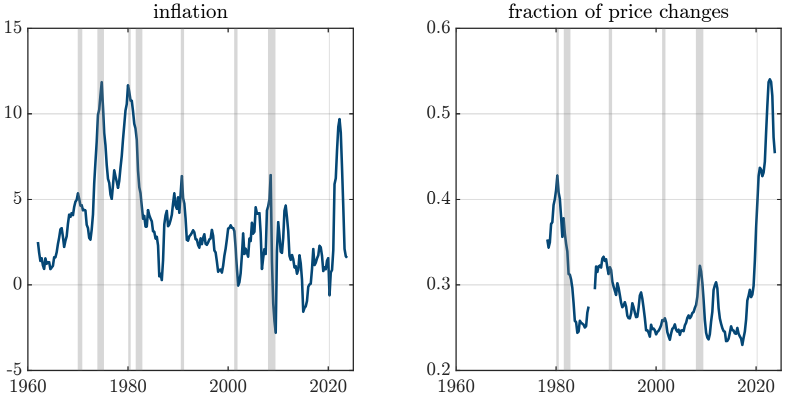
[1] The views expressed herein are those of the authors and not necessarily those of the Board of Governors of the Federal Reserve System, the Federal Reserve Bank of Atlanta or the Federal Reserve System.

Motivation

- Slope of Phillips curve key ingredient in monetary policy analysis
- In sticky price models pinned down by fraction of price changes
- Data: fraction of price changes increases with inflation
  - Gagnon (2009), Alvarez et al. (2018), Blanco et al. (2024)

Evidence from the U.S.



- Source: Nakamura et al. (2018), Montag and Villar (2023). Fraction quarterly.
- Inflation computed using CPI without shelter (year-to-year changes).

▸ extensive margin decomposition

Motivation

- Slope of Phillips curve key ingredient in monetary policy analysis
- In sticky price models, key determinant: fraction of price changes
- Data: fraction of price changes increases with inflation
  - Gagnon (2009), Alvarez et al. (2018), Blanco et al. (2024)
- How does slope fluctuate in the time series?
  - answer using model that reproduces this evidence

Existing Models

- Time-dependent models
  - widely used due to their tractability
  - constant fraction of price changes
- State-dependent models
  - less tractable: state of the economy includes distribution of prices
- We develop tractable alternative with endogenously varying fraction
  - multi-product firms choose *how many*, but not *which*, prices to change
  - exact aggregation: reduces to one-equation extension of Calvo

Our Findings

- Our model predicts highly non-linear Phillips curve
  - slope fluctuates from 0.02 in 1990s to 0.12 in 1970s and 1980s
- Part of increase ($0.02 \rightarrow 0.04$) due to higher fraction of price changes
- Most increase due to feedback loop between fraction and inflation
  - *inflation accelerator*
  - inflation more sensitive to changes in fraction when inflation is high

Model

- Consumers: log-linear preferences + CIA constraint
  - so $W_t = P_t c_t = M_t$
  - $\log M_{t+1}/M_t = \mu + \varepsilon_{t+1}$ only aggregate shock (robust to Taylor rule etc.)

- Multi-product firms i sell continuum of goods k each
  - final good sector competitive:

$$c_t = y_t = \left(\int_0^1 \int_0^1 (y_{ikt})^{\frac{\theta-1}{\theta}} \, \mathrm{d}k\mathrm{d}i \right)^{\frac{\theta}{\theta-1}}$$

  - demand for individual variety:

$$y_{ikt} = \left(\frac{P_{ikt}}{P_t} \right)^{-\theta} y_t, \qquad P_t = \left(\int_0^1 \int_0^1 (P_{ikt})^{1-\theta} \, \mathrm{d}k\mathrm{d}i \right)^{\frac{1}{1-\theta}}$$

  - each produced with DRS technology $y_{ikt} = (l_{ikt})^{\eta}$

Firm Problem

- Real discounted flow profits of firm i

$$\frac{1}{P_t c_t}\int_0^1 \left(P_{ikt} y_{ikt} - \tau W_t l_{ikt}\right) \mathrm{d}k = \left(\frac{P_{it}}{P_t}\right)^{1-\theta} - \tau\left(\frac{X_{it}}{P_t}\right)^{-\frac{\theta}{\eta}} y_t^{\frac{1}{\eta}}$$

  - flow profits depend on two moments of its price distribution

$$P_{it} = \left(\int_0^1 \left(P_{ikt}\right)^{1-\theta} \mathrm{d}k\right)^{\frac{1}{1-\theta}} \quad \text{and} \quad X_{it} = \left(\int_0^1 \left(P_{ikt}\right)^{-\frac{\theta}{\eta}} \mathrm{d}k\right)^{-\frac{\eta}{\theta}}$$

- Firm chooses fraction of price changes n_{it}, cost $\frac{\xi}{2}\left(n_{it} - \bar{n}\right)^2$ if $n_{it} > \bar{n}$

  - but not which, so history encoded in two state variables, P_{it-1} and X_{it-1}

  - e.g. $P_{it} = \left(n_{it}\left(P_{it}^{*}\right)^{1-\theta} + \left(1 - n_{it}\right)\left(P_{it-1}\right)^{1-\theta}\right)^{\frac{1}{1-\theta}}$

Symmetric Equilibrium

- Let $p_t^* = P_t^*/P_t$, $x_t = X_t/P_t$, $\pi_t = P_t/P_{t-1}$

- Optimal reset price similar to Calvo, except n_t varies

$$\left(p_t^*\right)^{1+\theta\left(\frac{1}{\theta}-1\right)} = \frac{1}{\eta}\frac{\left.\mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \left(y_{t+s}\right)^{\frac{1}{\eta}} \prod_{j=1}^{s} \left(1-n_{t+j}\right)\left(\pi_{t+j}\right)^{\frac{\theta}{\eta}} \right\} b_{2t}}{\left.\mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \prod_{j=1}^{s} \left(1-n_{t+j}\right)\left(\pi_{t+j}\right)^{\theta-1} \right\} b_{1t}}$$

- Fraction of price changes

$$\xi\left(n_t - \bar{n}\right) = \underbrace{b_{1t}\left(\left(p_t^*\right)^{1-\theta} - \left(\pi_t\right)^{\theta-1}\right)}_{\text{change price index}} - \underbrace{\tau b_{2t}\left(\left(p_t^*\right)^{-\frac{\theta}{\eta}} - \left(x_{t-1}\right)^{-\frac{\theta}{\eta}}\left(\pi_t\right)^{\frac{\theta}{\eta}}\right)}_{\text{reduce misallocation}}$$

Symmetric Equilibrium

- Inflation pinned down by the definition of price index

$$1 = n_t \left(p_t^*\right)^{1-\theta} + (1 - n_t)\left(\pi_t\right)^{\theta-1}$$

- Losses from misallocation

$$\left(x_t\right)^{-\frac{\theta}{\eta}} = n_t \left(p_t^*\right)^{-\frac{\theta}{\eta}} + (1 - n_t)\left(x_{t-1}\right)^{-\frac{\theta}{\eta}} \left(\pi_t\right)^{\frac{\theta}{\eta}}$$

- Model reduces to one-equation extension of Calvo
  - as $\xi \to \infty$, $n_t = \bar{n}$ so our model nests Calvo
- Unlike Calvo, important non-linearities so solve using global methods
  - third-order perturbation accurate

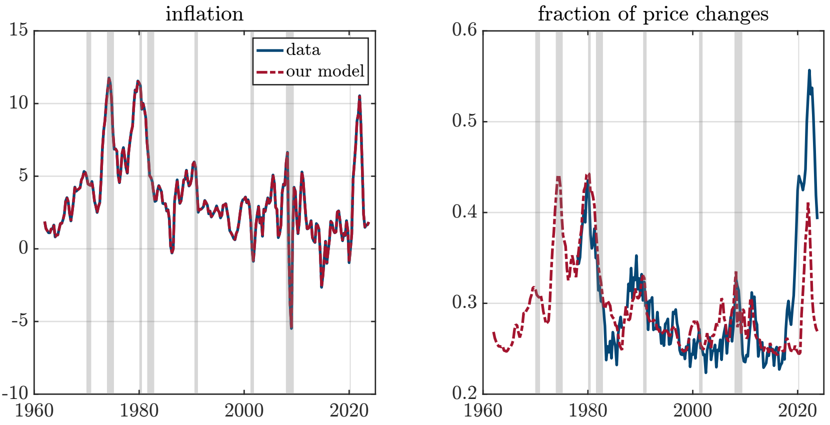
Parameterization

- Assigned parameters
  - period 1 quarter, $\beta = 0.99$, $\theta = 6$, $\eta = 2/3$
- Calibrated parameters
  - mean and standard deviation of money growth μ and σ
  - fraction of free price changes $\bar{n}$, price adjustment cost ξ
- Calibration targets

	Data	Model
mean inflation	0.035	0.035
s.d. inflation	0.027	0.027
mean fraction	0.297	0.297
slope of n_t on $\lvert\pi_t\rvert$	0.016	0.016

Fraction of Price Changes

- Use non-linear solution to recover shocks that reproduce U.S. inflation



- Reproduces fraction well, except post-Covid
  - many price decreases due to sectoral shocks

extensive margin model

Towards the Slope of the Phillips Curve

- First order perturbation around equilibrium point at each date t
  - hats denote deviations from equilibrium at that date

- Aggregate price index:

$$\hat{\pi}_t = \underbrace{\frac{1}{(1-n_t)\,\pi_t^{\theta-1}}\frac{\pi_t^{\theta-1}-1}{\theta-1}}_{\mathcal{M}_t}\hat{n}_t + \underbrace{\frac{1-(1-n_t)\,\pi_t^{\theta-1}}{(1-n_t)\,\pi_t^{\theta-1}}}_{\mathcal{N}_t}\hat{p}_t^*$$

- Elasticity $\mathcal{N}_t$ to reset price: identical to Calvo
  - increases with n_t, decreases with π_t (lower weight on new prices)

- Elasticity $\mathcal{M}_t$ to frequency: zero if $\pi_t = 1$, increases with inflation

Intuition

- Why is inflation more sensitive to changes in n_t when inflation is high?

$$\mathcal{M}_t = \frac{1}{(1-n_t)\,\pi_t^{\theta-1}} \frac{\pi_t^{\theta-1}-1}{\theta-1}$$

- Inflation $\approx$ average price change $\times$ fraction of price changes
  - $\pi_t = 1$: average price change $= 0$
    - so fraction inconsequential
  - π_t is high: average price change is large
    - so Δn_t increases inflation considerably

Inflation Accelerator

- Recall aggregate price index

$$\hat{\pi}_t = \mathcal{M}_t \hat{n}_t + \mathcal{N}_t \hat{p}_t^*$$

  - elasticity $\mathcal{M}_t$ increases with inflation, zero if $\pi_t = 1$

- Optimal fraction of price changes

$$\hat{n}_t = \mathcal{A}_t \hat{\pi}_t + \mathcal{B}_t \hat{p}_t^* - \mathcal{C}_t \hat{x}_{t-1} + \frac{n_t - \bar{n}}{n_t} \hat{b}_{1t}$$

  - elasticities $\mathcal{A}_t$ and $\mathcal{B}_t$ also increase with π_t

- Feedback loop amplifies inflation response to changes in reset price

$$\hat{\pi}_t = \frac{\mathcal{M}_t \mathcal{B}_t + \mathcal{N}_t}{1 - \mathcal{M}_t \mathcal{A}_t} \hat{p}_t^* - \frac{\mathcal{M}_t \mathcal{C}_t}{1 - \mathcal{M}_t \mathcal{A}_t} \hat{x}_{t-1} + \frac{\mathcal{M}_t}{1 - \mathcal{M}_t \mathcal{A}_t} \frac{n_t - \bar{n}}{n_t} \hat{b}_{1t}$$

Slope of the Phillips Curve

- Let $\widehat{mc}_t = \frac{1}{\eta}\hat{y}_t$ aggregate real marginal cost

$$\hat{\pi}_t = \mathcal{K}_t \widehat{mc}_t + \dots$$

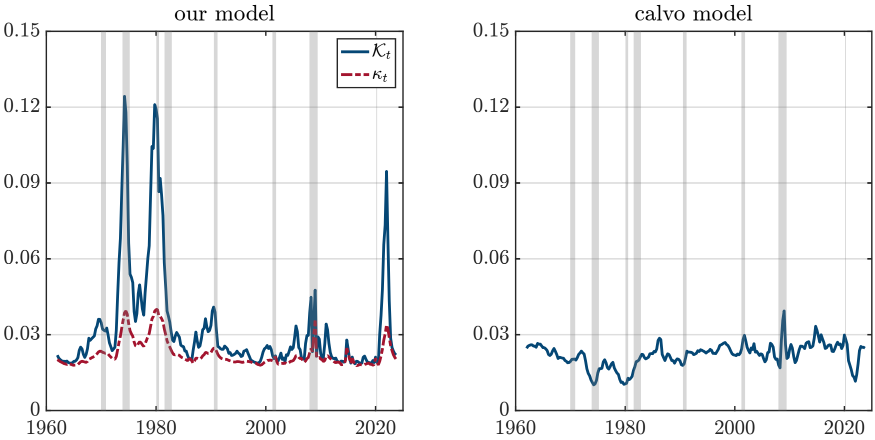
- Slope of the Phillips curve

$$\mathcal{K}_t = \underbrace{\frac{1}{1+\theta\left(\frac{1}{\eta}-1\right)}}_{\text{complementarities}} \quad \times \quad \underbrace{\frac{y_t^{\frac{1}{\eta}}}{b_{2t}}}_{\text{horizon}} \quad \times \quad \underbrace{\frac{\mathcal{M}_t\mathcal{B}_t+\mathcal{N}_t}{1-\mathcal{M}_t\mathcal{A}_t}}_{\text{reset price}}$$

- Absent endogenous frequency response ($\mathcal{A}_t = \mathcal{B}_t = 0$)

$$\kappa_t = \frac{1}{1+\theta\left(\frac{1}{\eta}-1\right)} \quad \times \quad \frac{y_t^{\frac{1}{\eta}}}{b_{2t}} \quad \times \quad \underbrace{\frac{1-(1-n_t)\,\pi_t^{\theta-1}}{(1-n_t)\,\pi_t^{\theta-1}}}_{\mathcal{N}_t}$$

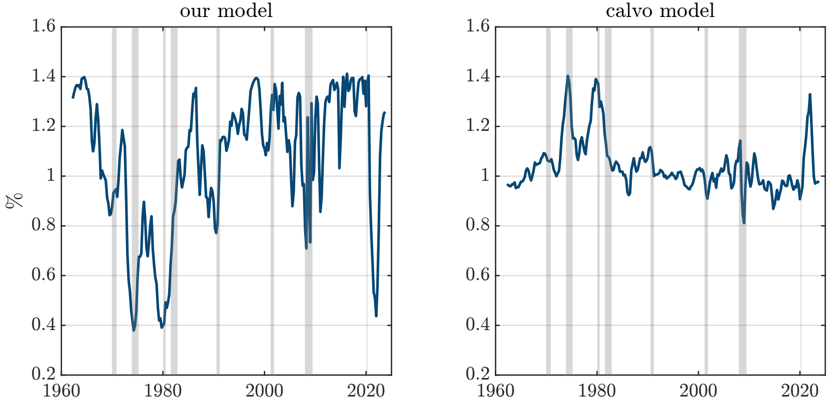
Time-Varying Slope of the Phillips Curve



Ranges from 0.02 to 0.12, mostly due to inflation accelerator

Sacrifice Ratio

- Calculate decline in annual output needed to reduce π by 1% over a year



Ranges from 0.4% to 1.4%, opposite of Calvo

Extensions

Three Practical Extensions

1. Idiosyncratic shocks ▸ idiosyncratic shocks
   - to match distribution of micro price changes
2. Taylor rule for monetary policy ▸ Taylor rule
   - standard in NK models
3. Multiple aggregate shocks ▸ aggregate shocks
   - to study drivers of inflation

- Robustness: the role of strategic complementarities ▸ $\eta = 1$

Conclusion

- Data: fraction of price changes increases with inflation
- Developed tractable model consistent with this evidence
  - firms choose how many, but not which prices to change
  - reduces to one-equation extension of Calvo
- Implies slope of Phillips curve increases considerably with inflation
  - partly because more frequent price changes
  - primarily due to endogenous frequency response – *inflation accelerator*

Robustness

Eliminate Strategic Complementarities

- Set $\eta = 1$, recalibrate model

Targeted Moments

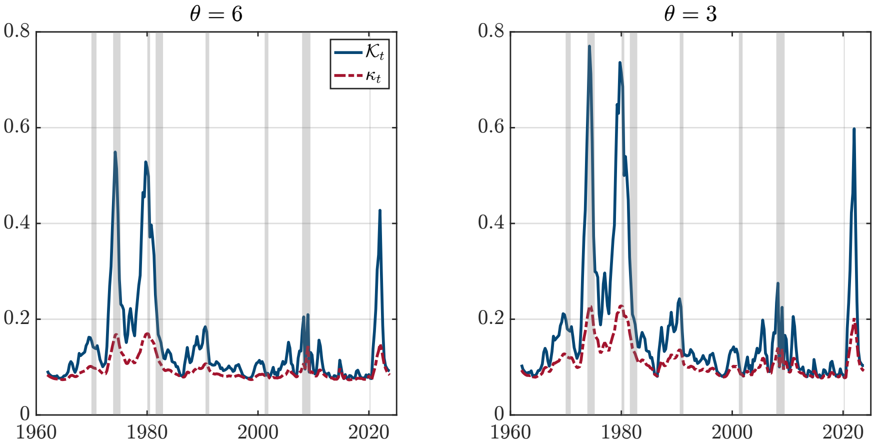
	Data	$\theta = 6$	$\theta = 3$
mean inflation	3.517	3.517	3.517
s.d. inflation	2.739	2.739	2.739
mean fraction	0.297	0.297	0.297
slope of n_t on $\|\pi_t\|$	0.016	0.016	0.016

Calibrated Parameters

		$\theta = 6$	$\theta = 3$
μ	mean spending growth rate	0.035	0.035
σ	s.d. monetary shocks	0.019	0.018
$\bar{n}$	fraction free price changes	0.232	0.227
ξ	adjustment cost	0.365	0.109

- Smaller price adjustment costs because less curvature in profit function

Slope of the Phillips Curve



Larger absent complementarities, but fluctuates as much

Taylor Rule

- Replace nominal spending target with Taylor rule

$$\frac{1+i_t}{1+i} = \left(\frac{1+i_{t-1}}{1+i}\right)^{\phi_i} \left(\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{y_t}{y_{t-1}}\right)^{\phi_y}\right)^{1-\phi_i} u_t$$

- Two versions
  - u_t shocks iid
  - serially correlated with persistence ρ to match autocorrelation inflation
- Use Justiniano and Primiceri (2008) estimates
  - $\phi_i = 0.65$, $\phi_\pi = 2.35$, $\phi_y = 0.51$

Calibration of Economy with a Taylor Rule

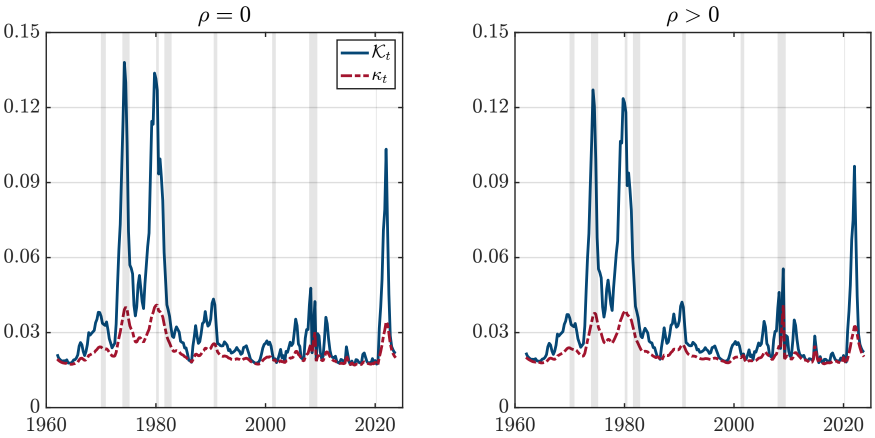
Targeted Moments

	Data	$\rho = 0$	$\rho > 0$
mean inflation	3.517	3.517	3.517
s.d. inflation	2.739	2.739	2.739
mean fraction	0.297	0.297	0.297
slope of n_t on $\lvert\pi_t\rvert$	0.016	0.016	0.016
autocorr. inflation	0.942	*0.913*	0.942

Calibrated Parameters

		$\rho = 0$	$\rho > 0$
$\log \pi$	inflation target	0.040	0.037
σ	s.d. monetary shocks $\times 100$	2.626	0.551
ρ	persistence money shocks	–	0.685
$\bar{n}$	fraction free price changes	0.241	0.241
ξ	adjustment cost	1.671	1.688

Slope of the Phillips Curve



Our results robust to assuming a Taylor rule

Losses from Misallocation

$$
\begin{aligned}
(X_{it+s})^{-\frac{\theta}{\eta}} = {} & n_{it+s} \left(P^*_{it+s}\right)^{-\frac{\theta}{\eta}} + (1 - n_{it+s})\, n_{it+s-1} \left(P^*_{it+s-1}\right)^{-\frac{\theta}{\eta}} + \cdots \\
& + \prod_{j=1}^{s} (1 - n_{it+j})\, n_{it} \left(P^*_{it}\right)^{-\frac{\theta}{\eta}} + \prod_{j=1}^{s} (1 - n_{it+j})\, (1 - n_{it})\, (X_{it-1})^{-\frac{\theta}{\eta}}
\end{aligned}
$$

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Steady-State Output and Productivity

$$y^{\frac{1}{\eta}} = \eta \frac{1-\beta(1-n)\pi^{\frac{\theta}{\eta}}}{1-\beta(1-n)\pi^{\theta-1}}\left(\frac{n}{1-(1-n)\pi^{\theta-1}}\right)^{\frac{1+\theta\left(\frac{1}{\eta}-1\right)}{\theta-1}}$$

$$x^{\theta} = \left(\frac{1-(1-n)\pi^{\frac{\theta}{\eta}}}{n}\right)^{\eta}\left(\frac{1-(1-n)\pi^{\theta-1}}{n}\right)^{-\frac{\theta}{\theta-1}}$$

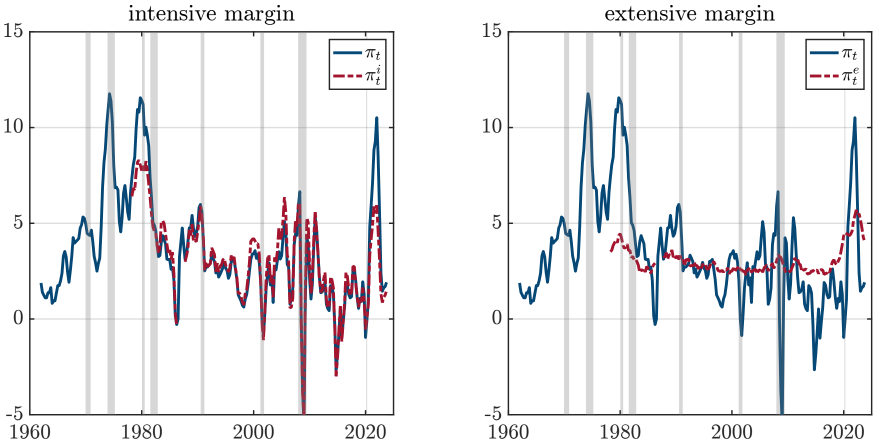
back

Role of Extensive Margin

- Decompose $\pi_t = \Delta_t n_t$ into two components
  - Δ_t : average price change conditional on adjustment
  - n_t : fraction of price changes

- Isolate role of each using Klenow and Kryvtsov (2008) decomposition
  - intensive margin: $\pi_t^i = \Delta_t \bar{n}$
    - $\bar{n}$: mean fraction of price changes
  - extensive margin: $\pi_t^e = \bar{\Delta} n_t$
    - $\bar{\Delta}$: mean average price change

Role of Extensive Margin: Data



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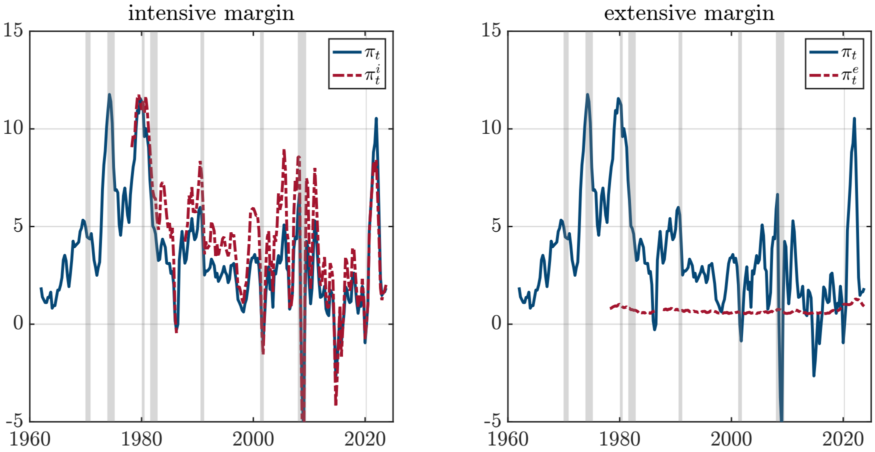
Montag and Villar (2024)

- Argue that extensive margin plays no role post Covid
- Same decomposition but set $\bar{n}$ and $\bar{\Delta}$ equal to January 2020 values
  - due to seasonality, unusually large n and low Δ
- Illustrate fixing $\bar{n}$ and $\bar{\Delta}$ at January 2020 values

Role of Extensive Margin using January 2020



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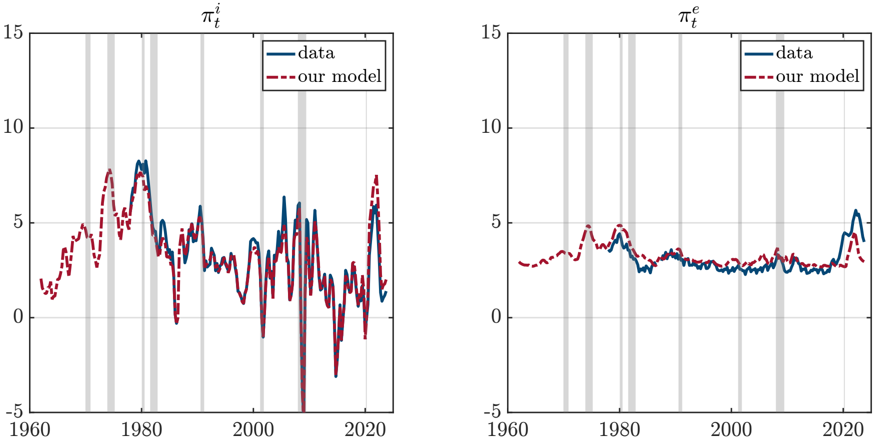
Role of Extensive Margin: Our Model



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Idiosyncratic Shocks

- Individual goods produced with technology

$$y_{ikt} = z_{ikt} l_{ikt}^{\eta}, \quad \text{where} \quad \log z_{ikt} = \log z_{ikt-1} + \sigma_z \epsilon_{ikt},\ \epsilon_{ikt} \sim N(0,1)$$

- Final output

$$y_t = \left(\int_0^1 \int_0^1 \left(\frac{y_{ikt}}{z_{ikt}} \right)^{\frac{\theta-1}{\theta}} \mathrm{d}k \mathrm{d}i \right)^{\frac{\theta}{\theta-1}}$$

- Firm price index P_{it} and misallocation X_{it} depend on $z_{ikt} P_{ikt}$

- Expressions similar to benchmark, with scaling terms that depend on σ_z
  - e.g., terms involving $\pi_t^{\theta-1}$ scaled by $\exp\left(\frac{\sigma_z^2}{2} (1-\theta)^2 \right)$

Calibration

- Because idiosyncratic shocks motive to change prices, assume $\bar{n} = 0$

A. Targeted Moments

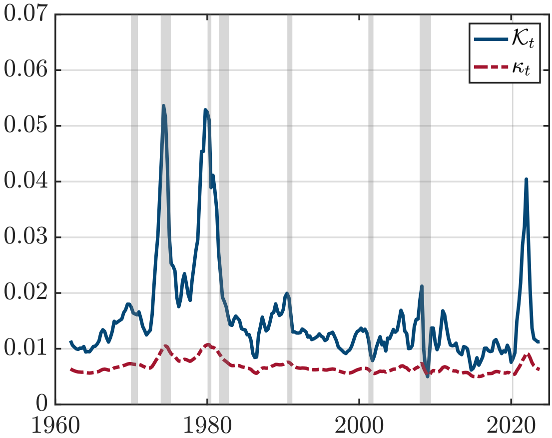
	Data	Model
mean inflation	3.517	3.517
s.d. inflation	2.739	2.739
mean frequency	0.297	0.297
slope of n_t on $\lvert\pi_t\rvert$	0.016	0.015
s.d. price changes	0.129	0.129

B. Calibrated Parameter Values

		Model
μ	mean spending growth rate	0.035
σ	s.d. monetary shocks	0.023
ξ	adjustment cost	17.00
σ_z	s.d. idiosyncratic shocks	0.068

Note: The mean nominal spending growth rate is annualized. S.d. of price changes is from Morales-Jimenez-Stevens (2024).

Slope of the Phillips Curve



Smaller with idiosyncratic shocks, but fluctuates as much

back

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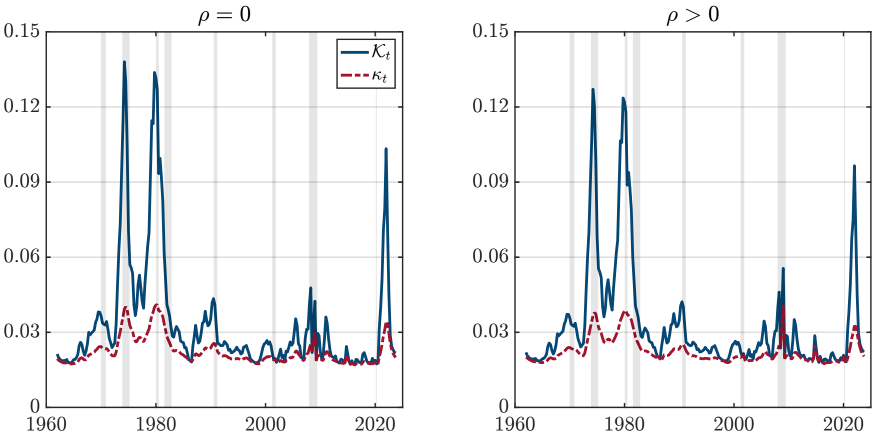

Results are robust to assuming a Taylor rule

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Additional Aggregate Shocks

- Three sources of aggregate uncertainty, all follow AR(1)
  - aggregate productivity shocks

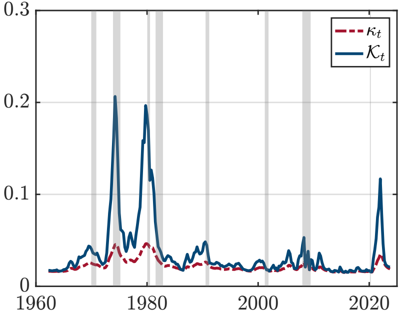
    $$y_{ikt} = z_t l_{ikt}^{\eta}$$

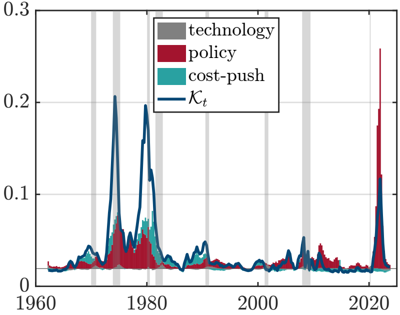
  - time-varying tax on labor (cost-push shock)

    $$P_{ikt} y_{ikt} - \tau_t W_t l_{ikt}$$

  - interest rate shocks in Taylor rule
- Bayesian estimation, as typical in NK literature
- Back out productivity, cost-push and monetary shocks
  - so that model matches path of inflation, output growth and interest rate
- Compute slope of Phillips curve as in bechmark

Slope of the Phillips Curve





Results are robust to adding multiple aggregate shocks

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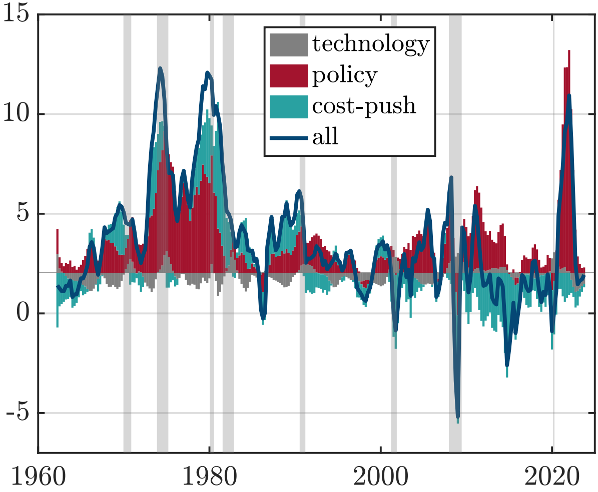
Causes of Inflation



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Eliminate Strategic Complementarities

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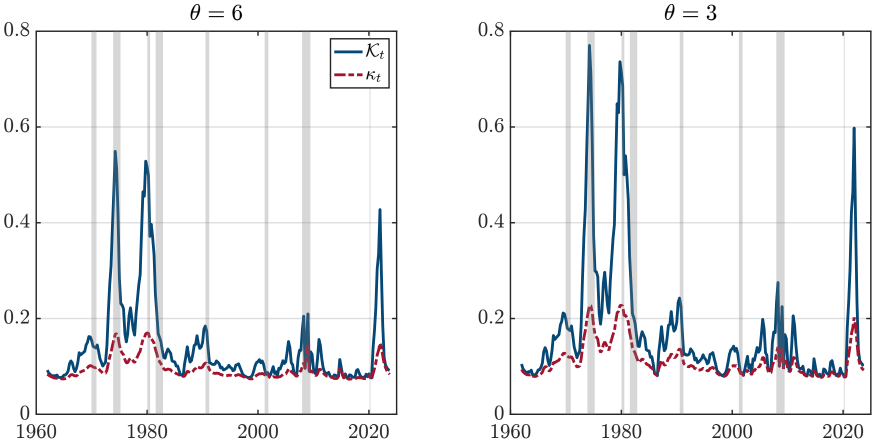

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