

# Endogenous Production Networks Under Supply Chain Uncertainty

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How does uncertainty affect an economy's production network and, through that channel, macroeconomic aggregates?

## Approach and results

We construct a model of **endogenous network formation** under **uncertainty**

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We **calibrate** the model to the United States economy

- Network flexibility has large impact on welfare
- Sizable role for uncertainty during high-volatility events like the Great Recession

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**Reduced-form evidence** for the model mechanisms

- Links with riskier suppliers are more likely to be destroyed
- Riskier firms have lower Domar weights

Economy

## As supply lines strain, some corporations rewrite production playbook

Many firms are eyeing regional networks to replace globe-circling supply chains

 Listen to article 8 min



Trucks line up to enter a Port of Oakland shipping terminal in Oakland, Calif. (Noah Berger/AP)

*“As the disruptions persist, executives are embracing more lasting measures, moving production to new suppliers or different countries and relaxing their traditional fixation with low costs.”*

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- COVID-19 pandemic: 70% agreed that the pandemic pushed companies to favor **higher supply chain resiliency** instead of purchasing from the lowest-cost supplier (Foley & Lardner, 2020)

### Uncertainty

- Bloom (2009); Fernandez-Villaverde et al (2011); Bloom (2014); Bloom et al (2018); and many others ...

### Exogenous production networks

- Long and Plosser (1983); Dupor (1999); Horvath (2000); Acemoglu et al (2012); Carvalho and Gabaix (2013); and many others ...

### Endogenous production networks

- Oberfield (2018); Acemoglu and Azar (2020); Boehm and Oberfield (2020); Taschereau-Dumouchel (2021); Acemoglu and Tahbaz-Salehi (2021); and many others ...

## Model

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Static model with two types of agents

1. **Representative household**: owns the firms, supplies labor and consumes
2. **Firms**: produce differentiated goods using labor and intermediate inputs
  - There are  $n$  industries/goods, indexed by  $i \in \{1, \dots, n\}$
  - Representative firm that behaves **competitively**

## Production technique

Each firm  $i$  has access to a set of production techniques  $\mathcal{A}_i$ .

A technique  $\alpha_i \in \mathcal{A}_i$  specifies

- The set of intermediate inputs to be used in production
- The proportions in which these inputs are combined
- A productivity shifter  $A_i (\alpha_i)$  for the firm

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These techniques are Cobb-Douglas production functions



- We identify  $\alpha_i = (\alpha_{i1}, \dots, \alpha_{in})$  with the input shares

$$F(\alpha_i, L_i, X_i) = e^{\varepsilon_i} \zeta(\alpha_i) A_i(\alpha_i) L_i^{1 - \sum_{j=1}^n \alpha_{ij}} \prod_{j=1}^n X_{ij}^{\alpha_{ij}},$$

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Allow adjustment along intensive and extensive margins:  $\mathcal{A}_i = \left\{ \alpha_i \in [0, 1]^n : \sum_{j=1}^n \alpha_{ij} \leq \bar{\alpha}_i < 1 \right\}$ .

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**Example:** A car manufacturer can use only steel or only carbon fiber, or a combination of both.

### Assumption

$A_i(\alpha_i)$  is smooth and strictly log-concave.

Implication: There are ideal input shares  $\alpha_{ij}^\circ$  that maximize  $A_i$

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### Example

$$\log A_i(\alpha_i) = - \sum_{j=1}^n \kappa_{ij} (\alpha_{ij} - \alpha_{ij}^\circ)^2 - \kappa_{i0} \left( \sum_{j=1}^n \alpha_{ij} - \sum_{j=1}^n \alpha_{ij}^\circ \right)^2,$$

## Source of uncertainty and timing

Firms are subject to **productivity shocks**  $\varepsilon = (\varepsilon_1, \dots, \varepsilon_n) \sim \mathcal{N}(\mu, \Sigma)$

- Vector  $\mu$  captures **optimism/pessimism** about productivity
- Covariance matrix  $\Sigma$  captures **uncertainty** and **correlations**

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### Timing

1. **Before  $\varepsilon$  is realized:** Production techniques are chosen
  - Beliefs  $(\mu, \Sigma)$  affect technique choice → production network  $\alpha \in \mathcal{A}$  is **endogenous**
2. **After  $\varepsilon$  is realized:** All other decisions are taken  
Only impact of uncertainty on decisions is through technique choice

▶ One tech.

## Household

The representative household makes decisions after  $\varepsilon$  is realized

- Owns the firms
- Supplies one unit of labor inelastically
- Chooses *state-contingent consumption*  $(C_1, \dots, C_n)$  to maximize

$$u \left( \left( \frac{C_1}{\beta_1} \right)^{\beta_1} \times \cdots \times \left( \frac{C_n}{\beta_n} \right)^{\beta_n} \right),$$

subject to the *state-by-state* budget constraint

$$\sum_{i=1}^n P_i C_i \leq 1,$$

where  $u$  is CRRA with relative risk aversion  $\rho \geq 1$ .

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▶ Details

- We refer to aggregate consumption  $Y = \prod_{i=1}^n (\beta_i^{-1} C_i)^{\beta_i}$  as GDP.

## Household

Two key quantities from the household's problem

1. The **stochastic discount factor** of the household is

$$\Lambda = u'(Y) / \bar{P}$$

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2. **log GDP as a function of prices**

$$y = -\beta' p,$$

where  $y = \log Y$ ,  $p = (\log(P_1), \dots, \log(P_n))$  and  $\beta = (\beta_1, \dots, \beta_n)$ .

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⇒ We only need prices to compute GDP

## Problem of the firm

Firms solve a two-stage problem

1. Before  $\varepsilon$  is drawn: Choose production technique  $\alpha_i$ 
  - ex ante decision under uncertainty
2. After  $\varepsilon$  is drawn: Choose inputs ( $L, X$ )

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## Problem of the firm: Labor and intermediate inputs

For a given technique  $\alpha_i$ , the **cost minimization** problem of the firm is

$$K_i(\alpha_i, P) = \min_{L_i, X_i} \left( L_i + \sum_{j=1}^n P_j X_{ij} \right), \text{ subject to } F(\alpha_i, L_i, X_i) \geq 1$$

where  $K_i(\alpha_i, P)$  is the **unit cost** of production.

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where  $K_i(\alpha_i, P)$  is the **unit cost** of production.

1. Constant returns to scale  $\rightarrow K_i$  does not depend on firm size
2. Given that each technique is Cobb-Douglas,

$$K_i(\alpha_i, P) = \frac{1}{e^{\varepsilon_i} A_i(\alpha_i)} \prod_{j=1}^n P_j^{\alpha_{ij}}.$$

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Firm  $i$  chooses a technique  $\alpha_i \in \mathcal{A}_i$  to maximize profits

$$\alpha_i^* \in \arg \max_{\alpha_i \in \mathcal{A}_i} E [\Delta Q_i (P_i - K_i (\alpha_i, P))]$$

where  $Q_i$  is the equilibrium demand for good  $i$  and  $\Delta$  is the SDF.

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### Lemma

In equilibrium, the technique choice of the representative firm in sector  $i$  solves

$$\alpha_i^* \in \arg \min_{\alpha_i \in \mathcal{A}_i} E[k_i(\alpha_i, \alpha^*)] + \text{Cov}[\lambda(\alpha^*), k_i(\alpha_i, \alpha^*)]. \quad (1)$$

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Firm  $i$  chooses a technique  $\alpha_i \in \mathcal{A}_i$  to maximize profits

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The firm prefers techniques with low

1. expected unit cost
2. unit cost when marg. utility is high → firm “inherits” the household’s risk aversion through  $\Delta$

## Problem of the firm: Production technique

We can expand the two terms to minimize

$$E [k_i (\alpha_i, \alpha^*)] = -a_i (\alpha_i) + \sum_{j=1}^n \alpha_{ij} E [p_j]$$

Firm prefers techniques with high TFP and low average input prices.

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Firm prefers techniques with low correlation with SDF.

In general  $\text{Corr} [\lambda, k_i] > 0 \rightarrow$  Minimize variance of  $k_i$

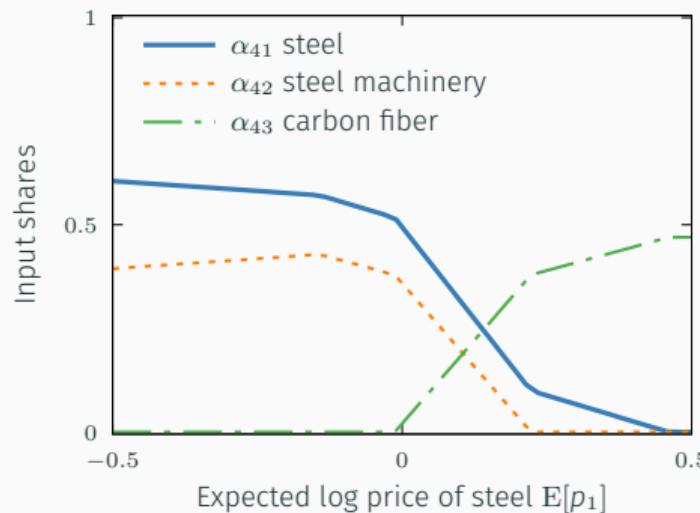
$$V[k_i] = \text{cte} + \underbrace{\sum_{j=1}^n \alpha_{ij}^2 V[p_j]}_{\text{stable prices}} + \underbrace{\sum_{j \neq k} \alpha_{ij} \alpha_{ik} \text{Cov}[p_j, p_k]}_{\text{uncorrelated prices}} + \underbrace{2 \text{Cov} \left[ -\varepsilon_i, \sum_{j=1}^n \alpha_{ij} p_j \right]}_{\text{uncorrelated with own } \varepsilon_i}$$

## Back to our car manufacturer example

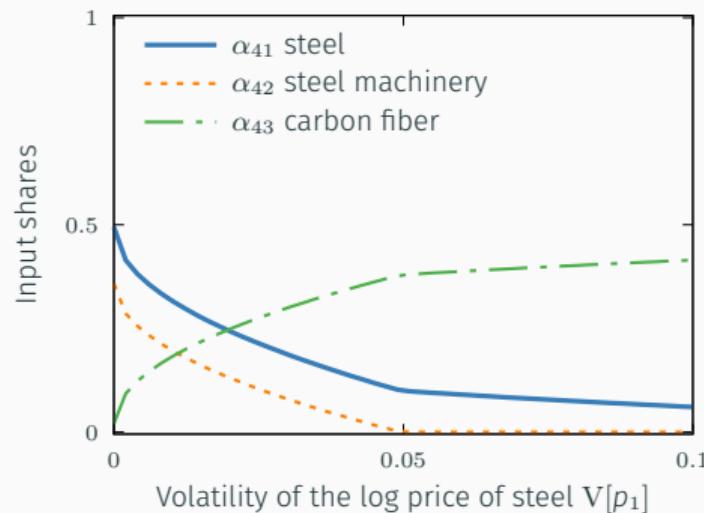
- Firm  $i = 4$  can use steel (input 1), steel milling machines (input 2) or carbon fiber (input 3)

$$a_4(\alpha_4) = - \sum_{j=1}^4 \kappa_j (\alpha_{4j} - \alpha_{4j}^\circ)^2 - \psi_1 (\alpha_{41} - \alpha_{42})^2 - \psi_2 ((\alpha_{41} + \alpha_{43}) - (\alpha_{41}^\circ + \alpha_{43}^\circ))^2,$$

(a) Impact of  $E[p_1]$  on input shares



(b) Impact of  $V[p_1]$  on input shares



## Definition

An equilibrium is a technique for every firm  $\alpha^*$  and a stochastic tuple  $(P^*, C^*, L^*, X^*, Q^*, \Lambda^*)$  such that

1. (Unit cost pricing) For each  $i \in \{1, \dots, n\}$ ,  $P_i^* = K_i(\alpha_i^*, P^*)$ .
2. (Optimal technique choice) For each  $i \in \{1, \dots, n\}$ , factor demand  $L_i^*$  and  $X_i^*$ , and the technology choice  $\alpha_i^* \in \mathcal{A}_i$  solves the firm's problem.
3. (Consumer maximization) The consumption vector  $C^*$  solves the household's problem.
4. (Market clearing) For each  $i \in \{1, \dots, n\}$ ,

$$Q_i^* = C_i^* + \sum_{j=1}^n X_{ji}^*,$$

$$Q_i^* = F_i(\alpha_i^*, L_i^*, X_i^*),$$

$$\sum_{i=1}^n L_i^* = 1.$$

## Fixed-network economy

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## GDP in a fixed-network economy

Define a firm's Domar weight  $\omega_i$  as its sales share

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Domar weights depend on

1. Demand from the household through  $\beta$
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### Lemma (Hulten's Theorem)

Under a given network  $\alpha$ , the log of GDP  $y = \log Y$  is given by

$$y = \omega(\alpha)' (\varepsilon + a(\alpha)).$$

## Impact of beliefs on GDP

Proposition (Hulten's Theorem in expectation)

For a **fixed network  $\alpha$** ,

1. The impact of  $\mu_i$  on expected log GDP is given by

$$\frac{\partial E[y]}{\partial \mu_i} = \omega_i.$$

2. The impact of  $\Sigma_{ij}$  on the variance of log GDP is given by

$$\frac{\partial V[y]}{\partial \Sigma_{ij}} = \omega_i \omega_j.$$

3.  $\mu$  does not affect  $V[y]$  and  $\Sigma$  does not affect  $E[y]$ .

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3.  $\mu$  does not affect  $V[y]$  and  $\Sigma$  does not affect  $E[y]$ .

For a **fixed network**

1. Domar weights  $\omega$  are enough to understand log GDP
2. Since  $\omega_i > 0$  shocks have intuitive impact.

## Flexible-network economy

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## Equilibrium and efficiency

The economy is **fully competitive** and **undistorted** by frictions or externalities.

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## Proposition

1. There exists a unique equilibrium and it is efficient.
2. That equilibrium production network solves

$$\mathcal{W} := \max_{\alpha \in \mathcal{A}} \mathbf{E}[y(\alpha)] - \frac{1}{2} (\rho - 1) \mathbf{V}[y(\alpha)]$$

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## Implications

1. The planner prefers networks that balance high  $\mathbf{E}[y(\alpha)]$  with low  $\mathbf{V}[y(\alpha)]$
2. Complicated network formation problem → simpler **optimization problem**.

## Recasting the planner's problem in the space of Domar weights

We can write the planner's problem as

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$$\mathcal{W} = \max_{\omega \in \mathcal{O}} \underbrace{\omega^\top \mu + \bar{a}(\omega)}_{E[y]} - \frac{1}{2} (\rho - 1) \underbrace{\omega^\top \Sigma \omega}_{V[y]}$$

## Economic forces at work

---

## Impact of beliefs on the network

Domar weights are constant when the network is fixed. But when it is flexible...

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The Domar weight  $\omega_i$  of firm  $i$  is increasing in  $\mu_i$  and decreasing in  $\Sigma_{ii}$ .

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Flexible network → beneficial changes are amplified while adverse changes are mitigated.

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Risk-adjusted productivity  $\mathcal{E}$ : measure of how higher exposure to  $\varepsilon$  affects the household's utility

$$\mathcal{E} = \underbrace{\mu}_{\text{E}[\varepsilon]} - \underbrace{(\rho - 1) \Sigma \omega}_{\text{Cov}[\varepsilon, \lambda]}$$

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The impact of a change in beliefs  $(\mu, \Sigma)$  can be summarized by its **direct** impact on  $\mathcal{E}$

$$\frac{\partial \mathcal{E}}{\partial \mu_i} = \mathbf{1}_i, \text{ and } \frac{\partial \mathcal{E}}{\partial \Sigma_{ij}} = -\frac{1}{2} (\rho - 1) (\omega_j \mathbf{1}_i + \omega_i \mathbf{1}_j)$$

## Impact of beliefs on the network

### Proposition

Let  $\gamma$  denote either  $\mu_i$  or  $\Sigma_{ij}$ . If  $\omega \in \text{int } \mathcal{O}$ , then

$$\frac{d\omega}{d\gamma} = \underbrace{-\mathcal{H}^{-1}}_{\text{propagation}} \times \underbrace{\frac{\partial \mathcal{E}}{\partial \gamma}}_{\text{impulse}},$$

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where  $\mathcal{H}$  is an  $n \times n$  matrix.

The matrix  $\mathcal{H}^{-1}$  captures **global substitution patterns** across sectors

1. If  $\mathcal{H}_{ij}^{-1} < 0$ ,  $i$  and  $j$  are **complements**: a beneficial shock to  $i$  (higher  $\mathcal{E}_i$ ) leads to an increase in  $\omega_j$
2. If  $\mathcal{H}_{ij}^{-1} > 0$ ,  $i$  and  $j$  are **substitutes**: a beneficial shock to  $i$  (higher  $\mathcal{E}_i$ ) leads to a decrease in  $\omega_j$

## Determinant of substitution patterns

$$\mathcal{H} = \nabla^2 \bar{a} - (\rho - 1) \Sigma$$

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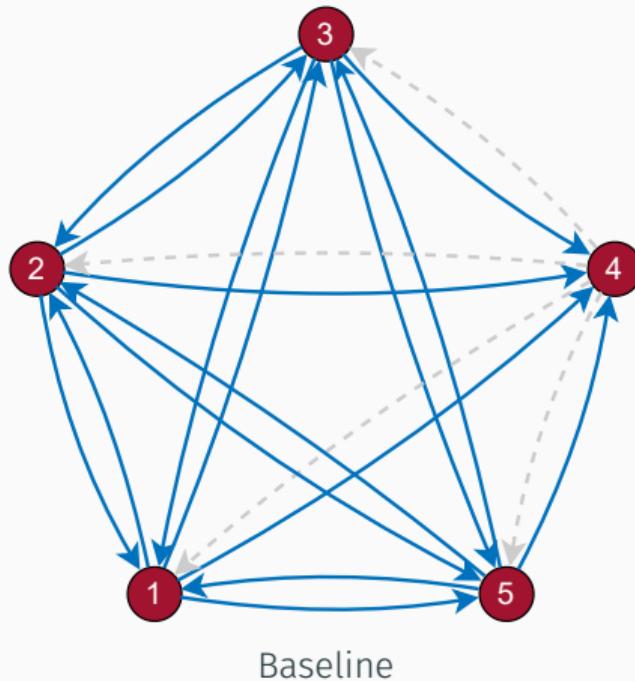
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1. Aggregate TFP shifter function  $\bar{a}$ 
  - Local substitution patterns in  $(a_1, \dots, a_n)$  contribute the global substitution patterns
2. Covariance matrix  $\Sigma$ 
  - If  $\Sigma_{ij}$  is larger the planner wants to lower  $\omega_j$  after an increase in  $\omega_i$  to reduce aggregate risk.

$$\frac{\partial \mathcal{H}_{ij}^{-1}}{\partial \Sigma_{ij}} > 0$$

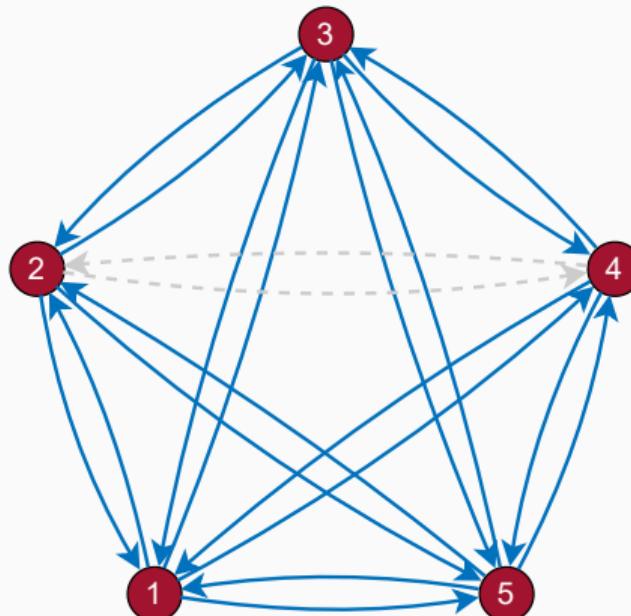
## Example: Impact of beliefs on the network

Simple example of possible substitution patterns



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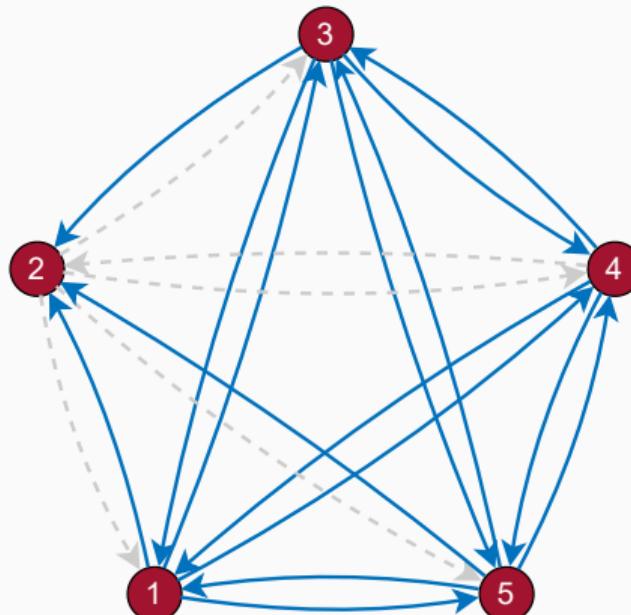
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Small increase in  $\Sigma_{22} \rightarrow$  Firms also purchase from 4 to diversify

## Example: Impact of beliefs on the network

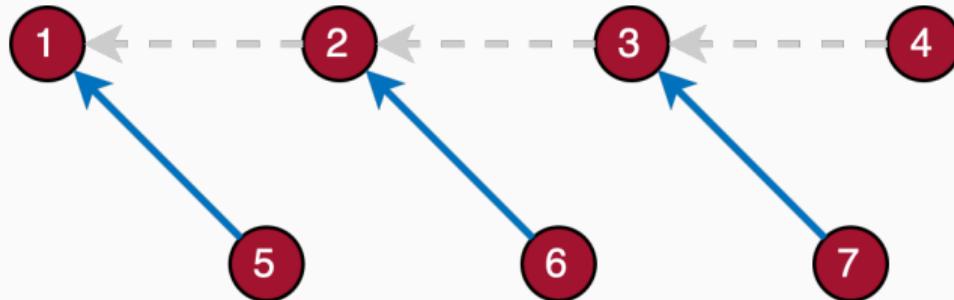
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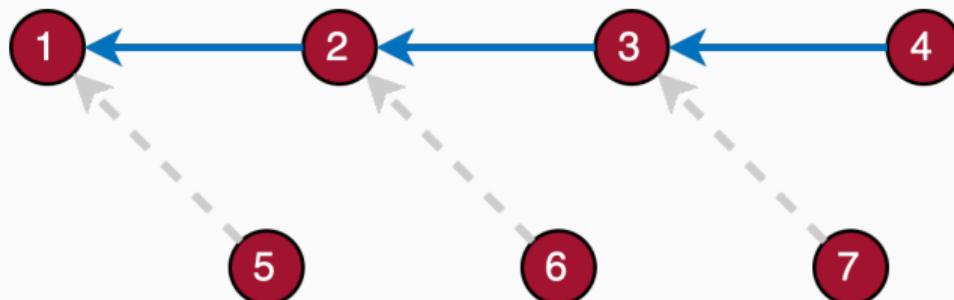
Large increase in  $\Sigma_{22} \rightarrow$  Firms drop 2 as a supplier

▶ Details

## Example: Cascading effect of uncertainty



(a) High uncertainty about  $\varepsilon_4$



(b) Low uncertainty about  $\varepsilon_4$

## Effect of beliefs on welfare

### Proposition

1. The impact of  $\mu_i$  on welfare is given by

$$\frac{d\mathcal{W}}{d\mu_i} = \omega_i.$$

2. The impact of  $\Sigma_{ij}$  on welfare is given by

$$\frac{d\mathcal{W}}{d\Sigma_{ij}} = -\frac{1}{2} (\rho - 1) \omega_i \omega_j$$

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The impact of beliefs on welfare is **intuitive**

1. Higher expected productivity increases welfare
2. Higher correlation or uncertainty lowers welfare

### Proposition

Uncertainty lowers expected GDP, in the sense that  $E[y]$  is largest when  $\Sigma = 0$ .

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## Intuition

1. **Equilibrium:** With uncertainty, firms seek stability at the cost of efficiency.
2. **Planner:** Only objective is to maximize  $E[y]$ .

$$\mathcal{W} := \max_{\alpha \in \mathcal{A}} E[y(\alpha)] - \frac{1}{2} (\rho - 1) V[y(\alpha)]$$

## Lemma

Let  $\gamma$  denote either  $\mu_i$  or  $\Sigma_{ij}$ . Then

$$\frac{d E[y]}{d \gamma} - \frac{\partial E[y]}{\partial \gamma} = \frac{1}{2} (\rho - 1) \left( \frac{d V[y]}{d \gamma} - \frac{\partial V[y]}{\partial \gamma} \right).$$

If the resp. of  $E[y]$  is better than under a fixed network, then the resp. of  $V[y]$  must be worse.

- Before the shock the planner was maximizing  $\rightarrow$  impossible to improve both  $E[y]$  and  $V[y]$

# Impact of a marginal change in beliefs

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## Lemma

Without uncertainty ( $\Sigma = 0$ ) Hulten's theorem holds, such that  $\frac{d E[y]}{d\mu_i} = \omega_i$  and  $\frac{d V[y]}{d\Sigma_{ij}} = \omega_i \omega_j$ .

- When  $\Sigma = 0$ , the equilibrium network maximizes expected log GDP  $\rightarrow \frac{d E[y]}{d\alpha} = 0$

## Impact of a marginal change in beliefs

### Lemma

Suppose that  $\omega \in \text{int } \mathcal{O}$ , that some condition on  $\Sigma$  holds and that all sectors are **global substitutes**, then

$$\frac{d E[y]}{d \mu_i} < \omega_i, \quad \text{and} \quad \frac{d V[y]}{d \mu_i} < 0.$$

and

$$\frac{d E[y]}{d \Sigma_{ij}} > 0, \quad \text{and} \quad \frac{d V[y]}{d \Sigma_{ij}} > \omega_i \omega_j.$$

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Intuition for an increase in  $\mu_i$

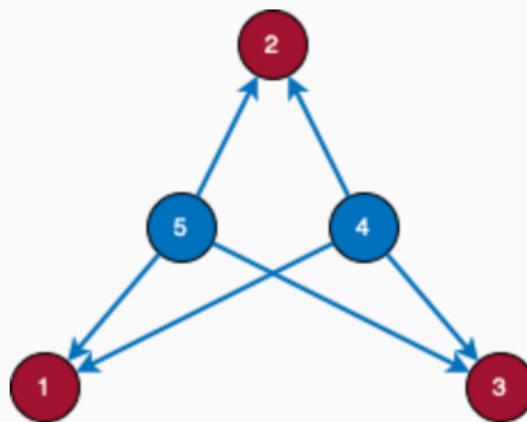
1. Because of the substitution, all  $\omega_j$  shrink for  $j \neq i$
2. If  $\Sigma_{jj}$  is large relative to  $\Sigma_{ii}$  than the variance of GDP  $V[y]$  decreases
3. By our earlier result,  $E[y]$  must grow by less than under a fixed network ( $\omega_i$ )

## Example: Counterintuitive impact of a change in $(\mu, \Sigma)$

Under some conditions, an increase in  $\mu_i$  can lead to a decline in  $E[y]$

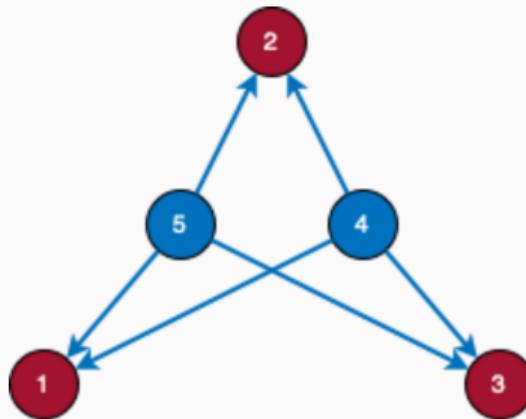
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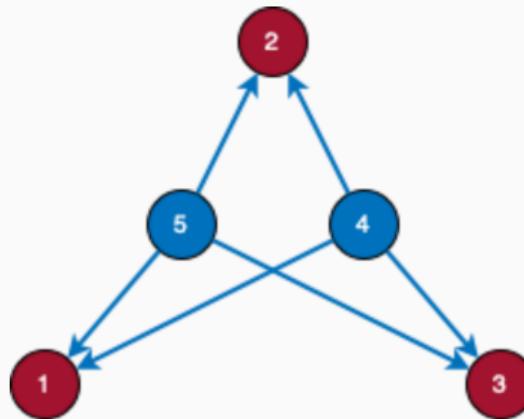
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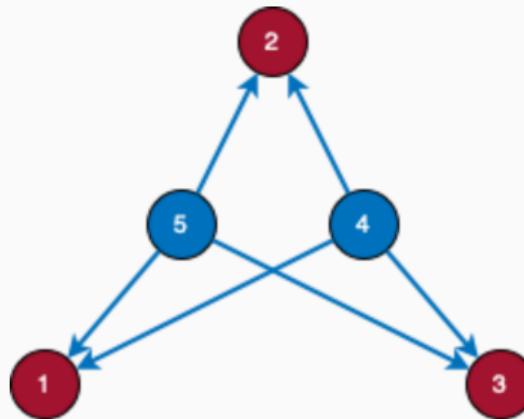
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- Firms 4 and 5 are **global substitutes** through local substitution in  $a_1, a_2$  and  $a_3$
- Firm 4 is **risky** (high  $\Sigma_{44}$ ) but **productive** (high  $\mu_4$ )
- Firm 5 is **safe** (low  $\Sigma_{55}$ ) but **unproductive** (low  $\mu_5$ )

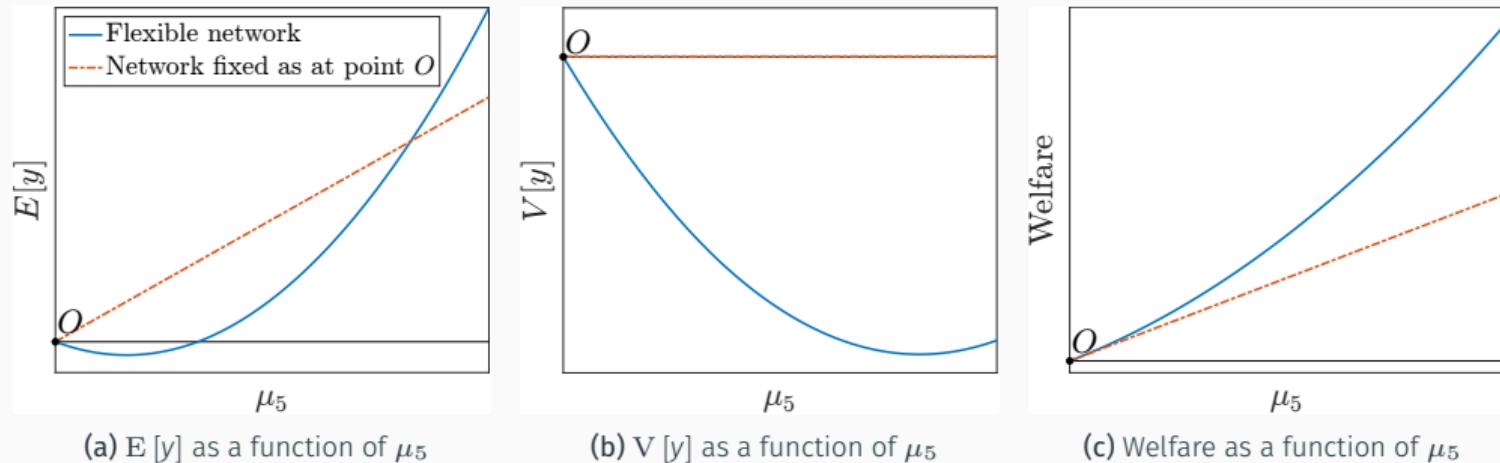
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- Increase  $\mu_5$ : Move away from high- $\mu$  firm 4 toward low- $\mu$  firm 5  $\Rightarrow E[y]$  falls

## Example: Counterintuitive impact of a change in $(\mu, \Sigma)$



## Quantitative exploration

---

## Data

- Annual United States data from 1947 to 2020 about 37 sectors

## Calibration

- Consumption shares  $\beta$  and ideal shares  $\alpha^o$  taken from the data
- Risk-aversion  $\rho$  and cost of deviating  $\kappa$  are **estimated**
- $\varepsilon_t$  is random walk with drift and **time-varying uncertainty** and is **estimated**

▶ Data details ▶ Estimation details

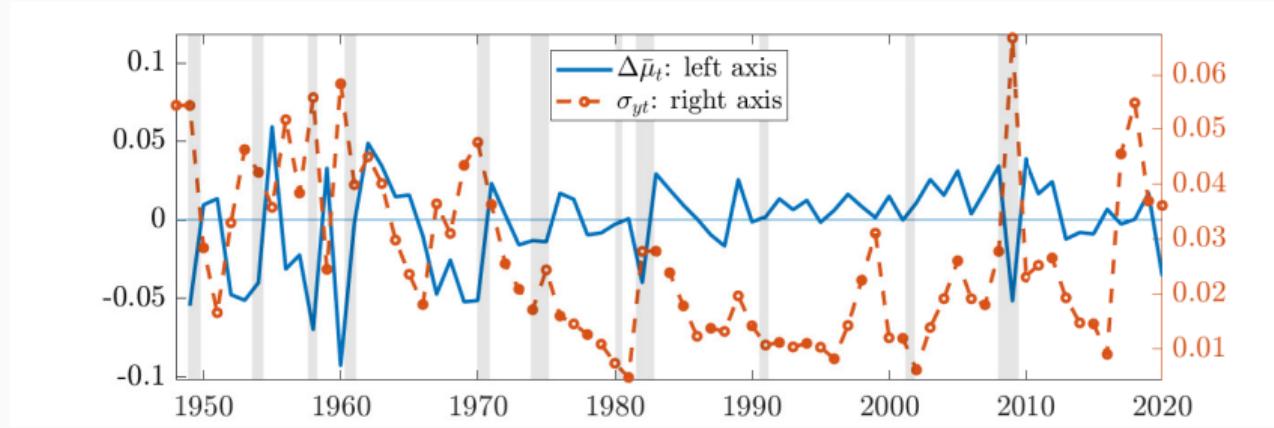
## Calibrated economy

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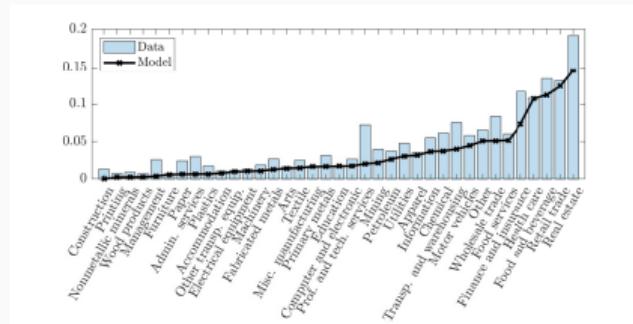
Estimated evolution of beliefs



$$\Delta\bar{\mu}_t = \sum_{j=1}^n \omega_{jt} \Delta\mu_{jt} \text{ and } \sigma_{yt} = \sqrt{V[y]} = \sqrt{\omega_t' \Sigma_t \omega_t}.$$

# Calibrated economy: Domar weights

The calibrated **Domar weights** fit the data reasonably well



Beliefs have the expected impact on **Domar weights**

	Statistic	Data	Model
(1)	Average Domar weight $\bar{\omega}_j$	0.047	0.032
(2)	Standard deviation $\sigma(\omega_j)$	0.0050	0.0021
(3)	Coefficient of variation $\sigma(\omega_j) / \bar{\omega}_j$	0.11	0.07
(4)	$\text{Corr}(\omega_{jt}, \mu_{jt})$	0.08	0.08
(5)	$\text{Corr}(\omega_{jt}, \Sigma_{jjt})$	-0.37	-0.31

# Isolating the mechanism

Two useful counterfactuals

## 1. Fixed-network economy

- No change in network → capture the full effect of network adjustments

## 2. “Risk-neutral” economy ( $\rho = 1$ )

- Uncertainty has no impact on network → capture the impact of uncertainty
- Recall: only impact of uncertainty on expected GDP is through the network

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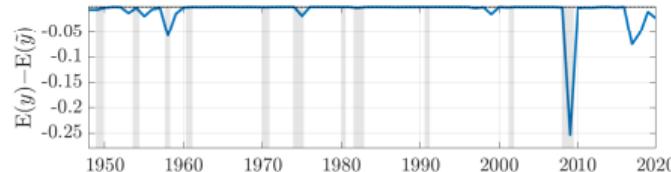
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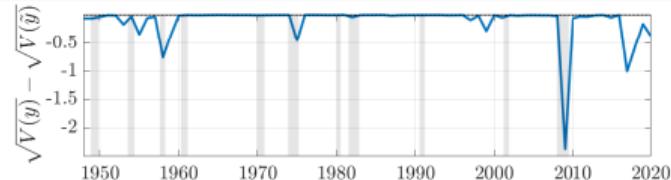
	Baseline model compared to...	
	Fixed network	Risk neutral
Expected GDP $E[y(\alpha)]$	+2.122%	-0.008%
Std. dev. of GDP $\sqrt{V[y(\alpha)]}$	+0.131%	-0.105%
Welfare $\mathcal{W}$	+2.109%	+0.010%

# The Great Recession

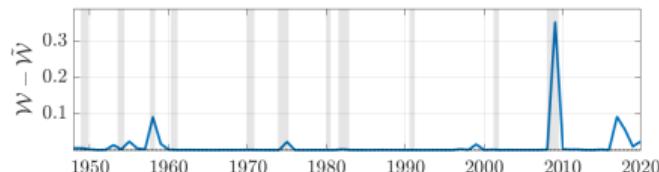
Calibrated model vs risk-neutral alternative



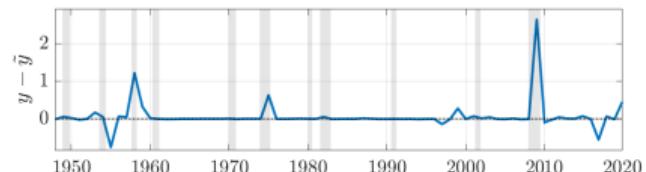
(a) Difference in expected GDP



(b) Difference in expected std. dev. of GDP



(c) Difference in expected welfare



(d) Difference in realized GDP

- During periods of **high volatility, uncertainty matters**.

## Reduced-form evidence for the model mechanisms

---

# Links with riskier suppliers are more likely to be destroyed

Use detailed U.S. data on **firm-to-firm relationship** (Factset 2003–2016)

Regress a dummy for **link destruction** on supplier **uncertainty measures**

- **Instruments** from Alfaro, Bloom and Lin (2019)

▶ Details

	Dummy for last year of supply relationship		
	(1) OLS	(2) IV	(3) IV
$\Delta \text{Vol}_{t-1}$ of supp.	0.026** (0.010)	0.097*** (0.029)	0.1494** (0.064)
1st moment of IVs	No	Yes	Yes
Type of volatility	Realized	Realized	Implied
Fixed effects	Yes	Yes	Yes
Observations	35,629	35,620	26,195
F-statistic	—	39.0	23.2

All specifications include year  $\times$  customer  $\times$  supplier industry (2SIC) fixed effects. Standard errors are two-way clustered at the customer and the supplier levels. F-statistics are Kleibergen-Paap. \*, \*\*, \*\*\* indicate significance at the 10%, 5%, and 1% levels, respectively.

- Doubling volatility  $\rightarrow$  12 p.p. increase in probability link destroyed (IV)

## Domar weights and uncertainty in the data

Firms with **higher uncertainty** have **lower Domar weights**, in line with the model

- Specifications, uncertainty measures and instruments from Alfaro, Bloom and Lin (2019)

	Change in Domar weight		
	(1) OLS	(2) IV	(3) IV
$\Delta \text{Volatility}_{i,t-1}$	-0.043*** (0.004)	-0.250*** (0.076)	-0.672*** (0.185)
1st moment of IVs	No	Yes	Yes
Type of volatility	Realized	Realized	Implied
Fixed effects	Yes	Yes	Yes
Observations	111,587	26,962	16,862
F-statistic	—	17.0	9.8

All specifications include year and firm fixed effects. Standard errors are clustered at the industry (3SIC) level. F-statistics are Kleibergen-Paap.  
\*, \*\*, \*\*\* indicate significance at the 10%, 5%, and 1% levels, respectively.

◀ Back

## Conclusion

---

# Conclusion

## Main contributions

- We construct a model in which **beliefs**, and in particular uncertainty, affect the **production network**.
- During periods of high **uncertainty** firms purchase from safer but less productive suppliers which leads to a **decline in GDP**.
- Mechanism might be **quantitatively** important during periods of **high uncertainty**.

## Future research

- Use firm-level data to calibrate the model — firm-to-firm network is more sparse and links are often broken.
- Use the model to evaluate the impact of uncertainty on **global supply chains**.

## More about the data

United States data from vom Lehn and Winberry (2021)

- Input-output tables, sectoral total factor productivity, consumption shares

Mining	Utilities	Construction
Wood products	Nonmetallic minerals	Primary metals
Fabricated metals	Machinery	Computer and electronic manuf.
Electrical equipment manufacturing	Motor vehicles manufacturing	Other transportation equipment
Furniture and related manufacturing	Misc. manufacturing	Food and beverage manufacturing
Textile manufacturing	Apparel manufacturing	Paper manufacturing
Printing products manufacturing	Petroleum and coal manufacturing	Chemical manufacturing
Plastics manufacturing	Wholesale trade	Retail trade
Transportation and warehousing	Information	Finance and insurance
Real estate and rental services	Professional and technical services	Mgmt. of companies and enterprises
Admin. and waste mgmt. services	Educational services	Health care and social assistance
Arts and entertainment services	Accommodation	Food services
Other services		

- Average share of 1.4% with standard deviation of 0.5% over time

# More about the estimation

## Preferences

- Consumption shares  $\beta$  are taken directly from the data
- Relative risk aversion  $\rho$  is **estimated**

## Production technique productivity shifters

- Function  $A_i$  as described earlier
- Set ideal shares  $\alpha_{ij}^o$  to their data average
- Costs  $\kappa_{ij}$  of deviating from  $\alpha_{ij}^o$  are **estimated**

## Process for exogenous shocks $\varepsilon_t$

- Random walk with drift  $\varepsilon_t = \gamma + \varepsilon_{t-1} + u_t^\varepsilon$ , with  $u_t^\varepsilon \sim \text{iid } \mathcal{N}(0, \Sigma_t)$ .
- Drift vec.  $\gamma$  and cov. mat.  $\Sigma_t$  are **backed out from the data given**  $(\rho, \kappa)$ .

**Loss function:** Target the full set of shares  $\alpha_{ijt}$  and the GDP growth.

◀ Back

## More about the calibration

- Random walk with drift  $\varepsilon_t = \gamma + \varepsilon_{t-1} + u_t$ , with  $u_t \sim \text{iid } \mathcal{N}(0, \Sigma_t)$ .
  - We estimate the vector  $\gamma$  by averaging  $\Delta\varepsilon_t = \varepsilon_t - \varepsilon_{t-1}$  over time
  - We estimate  $\Sigma_t$  as

$$\hat{\Sigma}_{ijt} = \sum_{s=1}^{t-1} \lambda^{t-s-1} u_{is} u_{js}$$

where  $\hat{\lambda} = 0.47$  is set to the sectoral average of the corresponding parameters of a GARCH(1,1) model estimated on each sector's productivity innovation  $u_{it}$

◀ Back

## Expression for $\zeta(\alpha_i)$

The function  $\zeta(\alpha_i)$  is

$$\zeta(\alpha_i) = \left[ \left( 1 - \sum_{j=1}^n \alpha_{ij} \right)^{1 - \sum_{j=1}^n \alpha_{ij}} \prod_{j=1}^n \alpha_{ij}^{\alpha_{ij}} \right]^{-1}$$

This functional form allows for a simple expression for the unit cost  $K$

 Back

# Microfoundation for "one technique" restriction and cost minimization

## Key restriction

Each firm/industry  $i$  can only adopt one production technique.

- Each industry  $i \in \{1, \dots, n\}$  has a continuum of firms  $l \in [0, 1]$ .
- Buyers use *shoppers* to purchase goods
  - Shoppers face an *information problem* and cannot differentiate between producers within an industry
  - Uniform allocation: each producer gets mass  $Q_i dl$  of shoppers
  - Shoppers from firm  $m$  in industry  $j$  faces average price  $\tilde{P}_i^{jm} = \int_0^1 \tilde{P}_{il}^{jm} dl$  for good  $i$ .
- When a shopper  $m$  from  $j$  meets a producer  $l$  from  $i \rightarrow$  Nash bargaining

$$\tilde{P}_{il}^{jm} - K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) = \gamma \left( B_i^{jm} - K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) \right)$$

- Technique choice problem

$$\max_{\alpha_i^l \in \mathcal{A}_i} E \left[ \Lambda \sum_{j=0}^n Q_{ji} dl \int_0^1 \gamma \left( B_i^{jm} - K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) \right) dm \right] \longrightarrow \min_{\alpha_i^l \in \mathcal{A}_i} E \left[ \Lambda Q_i K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) \right]$$

## Microfoundation for "one technique" restriction and cost minimization

- Take limit  $\gamma \rightarrow 0$

- Nash bargaining implies  $\tilde{P}_{il}^{jm} = K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) \rightarrow \tilde{P}_{il}^{jm}$  does not depend on  $j, m \rightarrow \tilde{P}_i^{jm} \equiv P_i$ .
- $K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) \rightarrow K_i \left( \alpha_i^l, P \right)$
- Cost minimization problem

$$\min_{\alpha_i^l \in \mathcal{A}_i} E \left[ \Lambda Q_i K_i \left( \alpha_i^l, \left\{ \tilde{P}_k^{il} \right\}_k \right) \right] \longrightarrow \min_{\alpha_i^l \in \mathcal{A}_i} E \left[ \Lambda Q_i K_i \left( \alpha_i^l, P \right) \right]$$

- We have the same pricing equation as in benchmark model with all firms in  $i$  choosing same technique

◀ Back

## Risk aversion and $\rho$

Given the log-normal nature of uncertainty  $\rho \leq 1$  determines whether the agent is risk-averse or not. To see this, note that when  $\log C$  normally distributed, maximizing

$$E [C^{1-\rho}]$$

amounts to maximizing

$$E [\log C] - \frac{1}{2} (\rho - 1) V [\log C].$$

◀ Back

## Impact of $\mu$ and $\Sigma$ for $\alpha$

### Assumption (Weak complementarity)

For all  $i \in \mathcal{N}$ , the function  $a_i$  is such that  $\frac{\partial^2 a_i(\alpha_i)}{\partial \alpha_{ij} \partial \alpha_{ik}} \geq 0$  for all  $j \neq k$ .

### Lemma

Let  $\alpha^* \in \text{int}(\mathcal{A})$  be the equilibrium network and suppose that the assumption holds. There exists a  $\bar{\Sigma} > 0$  such that if  $|\Sigma_{ij}| < \bar{\Sigma}$  for all  $i, j$ , there is a neighborhood around  $\alpha^*$  in which

1. an increase in  $\mu_j$  leads to an increase in the shares  $\alpha_{kl}^*$  for all  $k, l$ ;
2. an increase in  $\Sigma_{jj}$  leads to a decline in the shares  $\alpha_{kl}^*$  for all  $k, l$ ;
3. an increase in  $\Sigma_{ij}$  leads to a decline in the shares  $\alpha_{kl}^*$  for all  $k, l$ .

◀ Back

## Pentagon example: parameter value

Details of the simulation:

1.  $a$  function:  $\kappa$  equal to 1, except  $\kappa_{ii} = \infty$ ,  $\alpha^\circ$  are 1/10 except  $\alpha_{ii}^\circ = 0$ .
2.  $\rho = 5$ ,  $\beta = 0.2$ .  $\mu = 0.1$  except for  $\mu_4 = 0.0571$ .  $\Sigma = 0.3 \times I_{n \times n}$  in Panel (a).
3. Panel (b): same as Panel (a) except  $\text{Corr}(\varepsilon_2, \varepsilon_4) = 1$ .
4. Panel (c): same in Panel (a) except  $\Sigma_{22} = 1$ .

◀ Back

## Calibrated $\kappa$

We assume that  $\kappa = \kappa^i \times \kappa^j$  where  $\kappa^i$  is an  $n \times 1$  column vector and  $\kappa^j$  is an  $1 \times (n + 1)$  row vector.

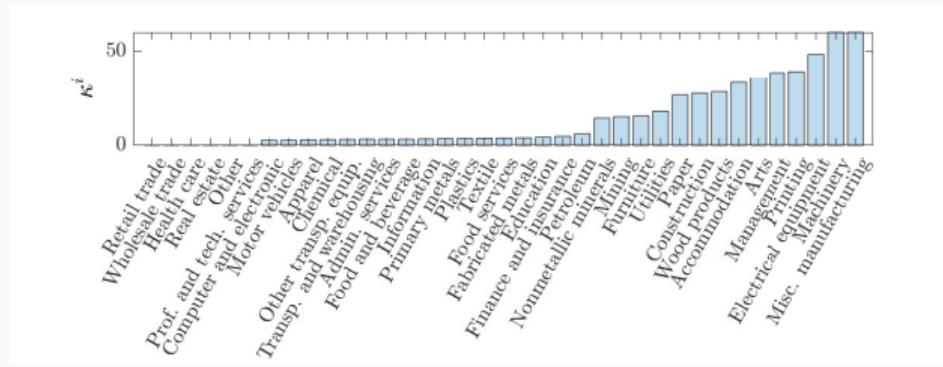
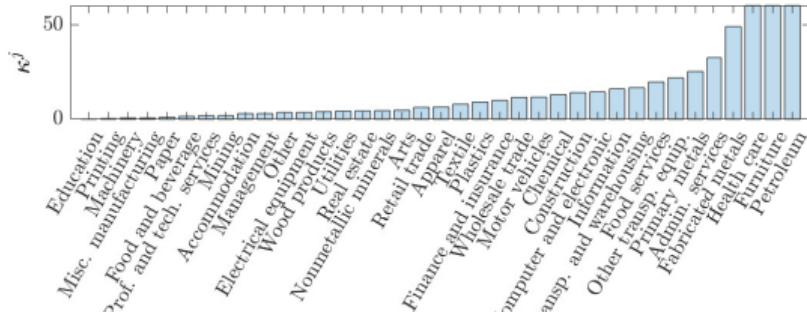


Figure 1: Vector of costs  $\kappa^i$



## Details of regressions

### Volatility measures

- Supplier  $\Delta Vol_{t-1}$  is the 1-year lagged change in supplier-level volatility.
- Realized volatility is the 12-month standard deviation of daily stock returns from CRSP.
- Implied volatility is the 12-month average of daily (365-day horizon) implied volatility of at-the-money-forward call options from OptionMetrics.

### Instrument

- As in Alfaro et al. 2019 “we address endogeneity concerns on firm-level volatility by instrumenting with industry-level (3SIC) non-directional exposure to 10 aggregate sources of uncertainty shocks. These include the lagged exposure to annual changes in expected volatility of energy, currencies, and 10-year treasuries (as proxied by at-the-money forward-looking implied volatilities of oil, 7 widely traded currencies, and TYYIX) and economic policy uncertainty from Baker et al 2016.. [...] To tease out the impact of 2nd moment uncertainty shocks from 1st moment aggregate shocks we also include as controls the lagged directional industry 3SIC exposure to changes in the price of each of the 10 aggregate instruments (i.e., 1st moment return shocks). These are labeled 1st moment 1st moment of IVs.”

◀ Back