The fragmentation of production amplifies systemic risk in supply chains

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Disruptions can propagate through supply chains

- Production disruptions **propagate through supply chains**
  - Empirical evidence (e.g., Barrot & Sauvagnat 2016)
  - Indirect losses of natural disasters often exceed direct loss (Hallegatte 2014)

- For businesses, a perception of rising **systemic risk**
  - Managers and insurers loosing track of risk propagation (e.g., Goldin 2010 & pers. commun.)
  - A quest for **supply chain resilience** in the business management literature (e.g., Sheffi 2005)
How fragmentation affect systemic risks?

- A trend towards global **outsourcing**
  1. **Complex** supply chains: more firms, more interconnected (Osadchiy et al. 2016)
     - Models linking network structure and disruption propagation (e.g., Coluzzi et al. 2011)
  2. **Fragmented** supply chains: production stages split between many firms (Hummels et al. 2001)
     - Gap: **How does fragmentation influence systemic risks?**

- Risk-management decisions are **interdependent** in supply chains
  - Decisions taken by one firm modify the risk exposure of the other firms
  - Operation-research models use **game theory** to elicit optimal strategies (Snyder et al. 2016)
  - Method limited to very small supply chains

- A stylized model with **evolutionary** dynamics
  - Supply chains subject to random disruption (e.g., Weisbuch & Battiston 2009)
  - Firms adapt their risk-mitigating strategy to the level of fragmentation
  - Evolutionary game on networks (Szabó & Fáth 2009) with coalitions
Model formulation, I — Input–output network

Connectivity matrix $M$

Final consumers, demand $d$

Raw materials, unlimited

**Technology:** Linear production function with productivity $z > 1$:

$z = 2$

Orders are equally split among suppliers (full substitutability).

**Risk mitigation:** Overorder at rate $\eta \geq 0$:

$\eta = 50\%$

Inventory with durability $\delta$: A fraction $\delta \geq 0$ of unused inputs is stored:

$\delta = 80\%$

**Shocks:** At each time step, firms get perturbed with probability $f$, called the failure rate.

$2.5 \times 0.8 = 2 \text{k€}$

$5 \text{k€}$

$10 \text{k€}$

$7.5 \text{k€}$

$2.5 \times 0.8 \times 0.8 = 2 \text{k€}$
Model formulation, II — Supply disruptions

We evaluate the average profit loss $L$ of the supply chain compared to a no-risk scenario.

$$L = \text{Direct Loss} + \text{Indirect Loss}$$

Loss incurred by firms that are externally perturbed

Loss due to the propagation of supply disruptions
The $n$ firms are allocated to $g$ groups
- Fragmentation = $(g - 1)/(n - 1)$

Each firm **adjust its overordering rate** $\eta_i$ to increase the profit of its group
- **Evolutionary** process based on gradient ascent
- Each firm **tries and tests** different rates and picks the one that increases profits
- The process is **iterated** until a stationary state is reached
Example of a fragmented chain, I — Differentiated strategies

Result

Productivity $z = 2$
Durability of inventory $\delta = 50\%$
Failure rate $f = 10\%$
Example of a fragmented chain, II — Risk mitigation

Relative reduction in indirect loss

Indirect loss ≈ 2*(Direct loss)

Indirect loss ≈ 1.2*(Direct loss)

Productivity \( z = 2 \)
Durability of inventory \( \delta = 50\% \)
Failure rate \( f = 10\% \)
Fragmentation amplifies systemic risks

Fragmentation diminishes risk mitigation...

...by reducing incentives to overorder
Supply chain mapping helps identify mitigation benchmarks

Suppose a decision-maker could impose the overordering rate based on objective criteria, what level of mitigation success could be reached?

Result
Supply chain mapping helps identify mitigation benchmarks

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Result
Concluding remarks

- **Fragmentation, inventories and risks**
  - More fragmented supply chains *(Hummels et al. 2001)* & lower inventories *(Goldin 2010)*
  - Our model suggests that **both trends may be linked**: fragmentation disincentivises inventories.
  - **Risks are transferred** from individual firms to the production system.

- **A coming role for insurers?**
  - There is a growing demand for **supply chain insurance** *(Munsch 2013 & pers. com.)*
  - Insurers inherit the complexity of the system.
  - **Supply chain mapping** helps provide benchmarks for mitigating risks.