The Economic Case for Global Vaccinations: An Epidemiological Model with International Production Networks

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NBER International Trade and Investment Program Meeting, Fall 2022

December 2-3, 2022

COVID-19 is a Global Crisis...

- ...Needs a global solution.
- Both economic and vaccine policies of rich countries are not aligned with this fact.
- A country can eliminate its own pandemic, but can still suffer from output losses through its global linkages if ROW has an ongoing pandemic.

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Key idea: COVID-19 constitutes a set of disaggregated sectoral demand and supply shocks that travel through global trade and production network

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- Estimate sectoral shocks for 65 countries and 35 sectors based on changes in sectoral consumption demand and labor supply as a function of infections.

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- Estimate sectoral shocks for 65 countries and 35 sectors based on changes in sectoral consumption demand and labor supply as a function of infections.
- Allow for endogenous lockdowns triggered by lack of vaccinations in EMDEs
  $\Rightarrow$ impact on AEs via a shortage of intermediate inputs, higher import prices, and weak demand for exports.

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- Provide upper and lower bound estimates for negative output effects of global supply chain disruptions, depending on the degree of complementarity across factors of production.

Two Shortages

January 28, 2021: Taiwan sought Germany's help in securing Covid-19 vaccines, after Berlin asked for the island's assistance in easing a shortage of automobile semiconductor chips.

$\Rightarrow$ Swap two vital shortages: The shortage of vaccines and the shortage of chips.

End of 2021: shortages spread to other sectors, leading to the highest levels of global inflation!

$\Rightarrow$ Persistence in supply chain disruptions was missed.

Early 2021

(a) Jan. 28, 2021

REUTERS

Taiwan asks Germany to help obtain coronavirus vaccines

By Reuters Staff — 2 MIN READ

TAIPEI (Reuters) - Taiwan has sought Germany's help in securing COVID-19 vaccines, Economy Minister Wang Mei-hua said on Thursday, after Berlin asked for the island's assistance in easing a shortage of automobile semiconductor chips.

(b) Jan. 9, 2021

THE WALL STREET JOURNAL.

Low on Workers, Manufacturers Recruit Their Executives for the Factory Floor

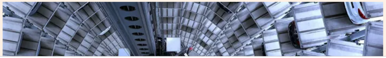
Covid, child care and competition from e-commerce warehouses contribute to labor shortages at many factories

(c) Feb. 28, 2021

FT FINANCIAL TIMES

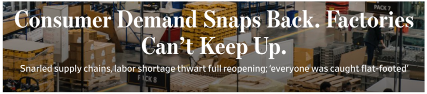
Carmakers braced for prolonged chip shortage

Executives warn supply is unlikely to meet demand in the first half of the year



(d) Feb. 22, 2021

THE WALL STREET JOURNAL.



Late 2021

(a) Aug. 25, 2021

FT FINANCIAL TIMES

Supply chains are a mess. So how come trade is booming?

At first glance, the economic headlines make for some mixed messages

(b) Oct. 31, 2021

FT FINANCIAL TIMES

Opinion **The FT View** + Add to myFT

Supply chain disruptions are now holding back the recovery

Central banks are ill-equipped to counter the bottleneck slowdown

THE EDITORIAL BOARD + Add to myFT

(c) Nov. 10, 2021

FT FINANCIAL TIMES

German economic recovery stumbles as Covid cases hit record high

Rising infections compound supply chain problems, driving forecast growth to among the eurozone's lowest

(d) Oct. 22, 2021

The New York Times

How the Supply Chain Broke, and Why It Won't Be Fixed Anytime Soon

Confession: We didn't even have a logistics beat before the pandemic. Now we do. Here's what we've learned about the global supply chain disruption.

Recent–China Lockdown

(a) May 9, 2022

FINANCIAL TIMES

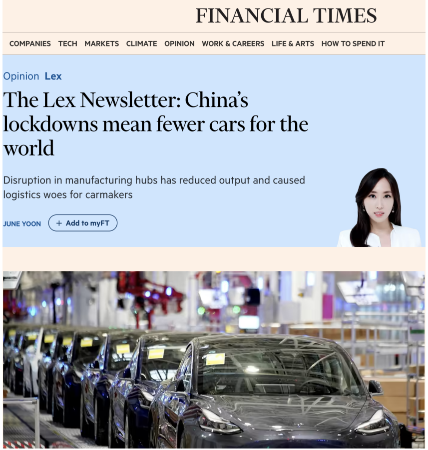
COMPANIES TECH MARKETS CLIMATE OPINION WORK & CAREERS LIFE & ARTS HOW TO SPEND IT

Chinese trade + Add to myFT

China's exporters battered by lockdowns and global inflation

Premier Li Keqiang sounds alarm over jobs despite Beijing's zero-Covid drive

(b) May 11, 2022



FINANCIAL TIMES

COMPANIES TECH MARKETS CLIMATE OPINION WORK & CAREERS LIFE & ARTS HOW TO SPEND IT

Opinion Lex

The Lex Newsletter: China's lockdowns mean fewer cars for the world

Disruption in manufacturing hubs has reduced output and caused logistics woes for carmakers

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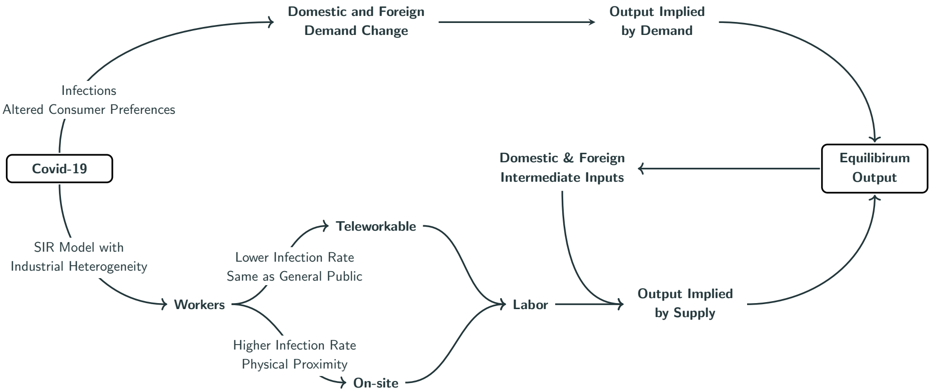
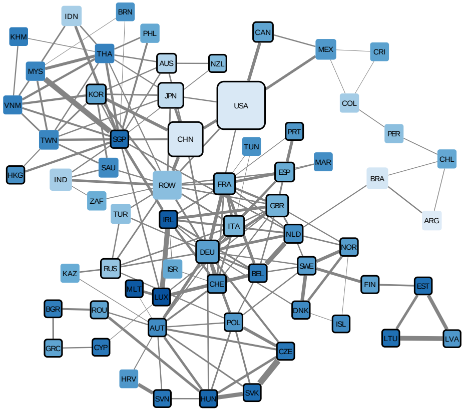
Sectoral Disease Heterogeneity Meets Global Sectoral Linkages

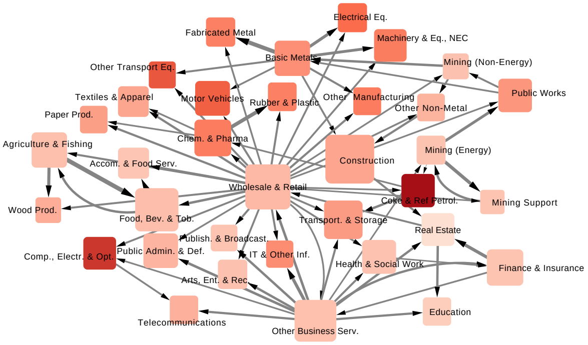


Global Trade and Production Network: OECD ICIO Tables

(a) International Trade Linkages



(b) Inter-industry Trade Linkages



35 industries in 65 countries, giving us a matrix of 2275 $\times$ 2275 entries

Model

Setup

- COVID-19: disaggregated sectoral demand and supply shocks

- Baqaee & Farhi (2022a)—sectoral supply and demand shocks in a closed economy and Baqaee & Farhi (2022b) + entire room here—**global network and international trade**.
  - Long and Plosser (1983), Horvath (1998), Acemoglu et al. (2012), Carvalho et al. (2016), Caliendo and Parro (2015), Barrot and Sauvagnat (2016), Atalay (2017), Caliendo et al. (2017), Kikkawa et al. (2017), Liu (2017), Morrow and Trefler (2017), Boehm et al. (2017), Baqaee (2018), Carvalho and Tahbaz-Salehi (2018), di Giovanni et al., (2018), Fally and Sayre (2018), Fieler and Harrison (2018), Tintelnot et al. (2018), Bernard et al. (2019), Boehm et al. (2019), Huo et al. (2020), Carvalho et al. (2021), , di Giovanni et al., (2022) . . .

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  Similarly:
  - Multiple sectors and factors, I-O linkages $\Rightarrow$ Multi-layer nested CES.
  - Segmented labor markets.

  Differently:
  - No hand-to-mouth consumers.
  - Flexible prices and wages.
  - No aggregate demand and/or tariff shock.

Final Production

- Combines labor and intermediate input bundle.
- Intermediate input bundle uses sector specific industry bundles.
- Industry bundles are aggregates of varieties from different countries.
    - German car industry uses steel that comes from Turkey, China, the US. Germans bundle these steels with high elasticity of substitution – Substitutes (Baseline).
    - German car industry uses steel bundles, plastic bundles, etc. that are complements, combines with other factors also with a low elasticity – Both complements (Baseline).

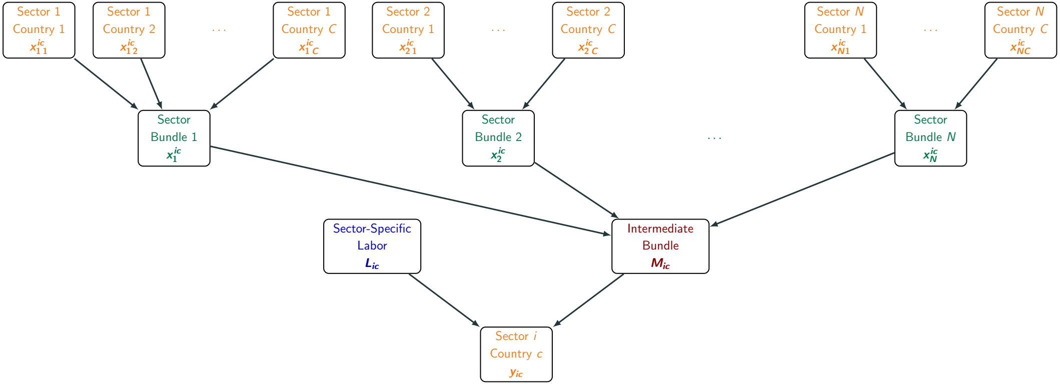
Input-Output Linkages

Inputs from industry j of country m to be used in producing industry i good in country c.

$$\Omega_{jm}^{ic} = \frac{p_{jm}^{c} x_{jm}^{ic}}{p_{ic} y_{ic}}.$$

- p_{ic}: price of good i in home country c.
- y_{ic}: Total output of industry i in home country c.
  - $i = 0$: final consumption. p_{0c}: consumption price index. y_{0c}" the total consumption of country c.
- x_{jm}^{ic}: input from industry j from country m used in industry i in country c.
- p_{jm}: price of j from country m.
- Factors denoted with f. Level L_f, wage w_f.
- Expenditure: $E_c = \sum_{f \in \mathcal{F}_c} w_f L_f$.
- Real GDP: $\text{GDP}_c = E_c / p_{0c}$

Production



Sector 1 Country 1 $x^{ic}_{1\,1}$
Sector 1 Country 2 $x^{ic}_{1\,2}$
...
Sector 1 Country C $x^{ic}_{1\,C}$
Sector 2 Country 1 $x^{ic}_{2\,1}$
...
Sector 2 Country C $x^{ic}_{2\,C}$
Sector N Country 1 x^{ic}_{N1}
...
Sector N Country C x^{ic}_{NC}
Sector Bundle 1 x^{ic}_{1}
Sector Bundle 2 x^{ic}_{2}
...
Sector Bundle N x^{ic}_{N}
Sector-Specific Labor L_{ic}
Intermediate Bundle M_{ic}
Sector i Country c y_{ic}

Production

Output of country-sector *ic*:

$$y_{ic} = \frac{A_{ic}}{\bar{A}_{ic}} \left[\alpha_{ic} \left(\frac{L_{ic}}{\bar{L}_{ic}} \right)^{\frac{1-\phi}{\phi}} + (1 - \alpha_{ic}) \left(\frac{M_{ic}}{\bar{M}_{ic}} \right)^{\frac{1-\phi}{\phi}} \right]^{\frac{\phi}{1-\phi}} .$$

Price of country-sector *ic*:

$$p_{ic} = \left[\alpha_{ic} \left(w_{ic} \right)^{1-\phi} + (1 - \alpha_{ic}) \left(p_M^{ic} \right)^{1-\phi} \right]^{\frac{1}{1-\phi}} .$$

- $0 \leq \phi \leq 1$: EoS between factors and intermediate bundle; labor and inputs are complements.
- p_M^{ic}: Price of intermediate bundle.
- α_{ic}: value-added share.

$$\alpha_{ic} = 1 - \sum_{jm \in \mathcal{N}} \Omega_{jm}^{ic}.$$

Intermediate Bundle

- Price of intermediate bundle that consists of sector bundles used by sector-country ic:

$$p_M^{ic} = \left[\sum_{j \in \mathcal{N}} \frac{\Omega s_j^{ic}}{1 - \alpha_{ic}} \left(p_j^{ic} \right)^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}},$$

  - $0 \leq \varepsilon \leq 1$: EoS for intermediate bundle; steel and plastic sectors are complements.
  - Ωs_j^{ic} captures the share of sector j in production of ic.
  - Ωs_j^{ic} is calculated by summing over the country varieties.

$$\Omega s_j^{ic} \equiv \sum_{m \in \mathcal{C}} \Omega_{jm}^{ic}$$

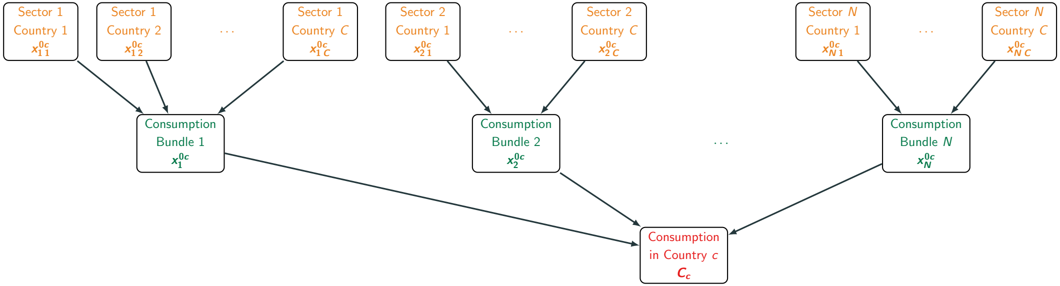
Sector Bundles

- Sector bundles are aggregates of varieties coming from different countries, with price:

$$p_j^{ic} = \left[\sum_{j \in \mathcal{N}} \frac{\Omega_{jm}^{ic}}{\Omega s_j^{ic}} \left(p_{jm}^{c} \right)^{1-\xi_i} \right]^{\frac{1}{1-\xi_i}}$$

  - $\xi_i \geq 1$, trade elasticity (production side)—Costinot & Rodriguez-Clare (2014), Caliendo & Parro (2015).
  - Our empirical implementation uses a range of $\varepsilon \leq \xi_i \leq 1$ & $\xi_i \geq 1$.
  - Germany can substitute steel from Turkey with steel from China or use them as complements (LR vs SR—Boehm, Flaaen, Pandalai-Nayar, 2019).

Consumption



Consumption

- 2-period optimization problem

- No aggregate shocks, sectoral shocks are unanticipated, intertemporal problem is reduntant.

- Within period: Consumer in country c consumes sector specific consumption bundles:

$$C_c = \left[\sum_{j \in \mathcal{N}} \Omega s_j^{0c} \left(x_j^{0c} \right)^{\frac{\sigma - 1}{\sigma}} \right]^{\frac{\sigma}{\sigma - 1}},$$

- Price for consumption bundle:

$$p_{0c} = \left[\sum_{j \in \mathcal{N}} \Omega s_j^{0c} \left(p_j^{0c} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}.$$

  - $\sigma = 1$, Cobb-Douglas, baseline calibration.
  - Ωs_j^{0c}: Share of industry j in final consumption of consumers in country c.

$$\Omega s_j^{0c} \equiv \sum_{m \in \mathcal{C}} \Omega_{jm}^{0c}$$

Consumption Bundles

- Consumption bundles are made of varieties from different countries.

$$x_j^{0c} = \left[\sum_{m \in \mathcal{C}} \frac{\Omega_{jm}^{0c}}{\Omega_j^{0c}} \left(x_{jm}^{0c} \right)^{\frac{\xi_j'-1}{\xi_j'}} \right]^{\frac{\xi_j'}{\xi_j'-1}} .$$

- The price equation for consumption bundle j of country c is:

$$p_j^{0c} = \left[\sum_{m \in \mathcal{C}} \frac{\Omega_{jm}^{0c}}{\Omega_j^{0c}} \left(p_{jm}^{c} \right)^{1-\xi_i'} \right]^{\frac{1}{1-\xi_i'}} .$$

- $\xi_i' \geq 1$, trade elasticity (consumption side), from Caliendo & Parro (2015).
- Also use $\xi_i' < 1$, via Boehm, Levchenko, Pandalai-Nayar (2022).
- Use same ξ_i' elasticity as sector bundles in the production side (baseline) and robustness when they differ: Consumption-$\xi_i' > 1$, Production-$\xi_i < 1$

Equilibrium

- Cost minimization, utility maximization and market clearing: Good prices, factor prices, outputs, inputs, and consumption.

- Good markets clear such that for any industry *ic*:

$$y_{ic} = \sum_{m \in \mathcal{C}} \sum_{j \in \mathcal{N}} x_{ic}^{jm} + \sum_{m \in \mathcal{C}} x_{ic}^{0m}. \tag{1}$$

- Labor markets clear: all "potential" sector-specific workers are employed.

- Initially, we set all prices to 1 and all output of country-sector pairs to their respective share in the total nominal world expenditure.

- After perturbing with shocks, the prices and outputs will re-equilibriate.

Solving the model

- Using small shock perturbation à la Baqaee and Farhi (2019, 2022b).

- Domar weights (E is the world expenditure, χ_c is country share):

$$\lambda_{jm} \equiv \frac{p_{jm}y_{jm}}{E} = \sum_{c\in\mathcal{C}} \frac{p_{jm}x_{jm}^{0c}}{E_c}\frac{E_c}{E} + \sum_{kc\in\mathcal{CN}} \frac{p_{jm}x_{jm}^{kc}}{E}$$
$$= \sum_{c\in\mathcal{C}} \Omega_{jm}^{0c}\chi_c + \sum_{kc\in\mathcal{CN}} \Omega_{jm}^{kc}\frac{p_{kc}y_{kc}}{E} = \sum_{c\in\mathcal{C}} \Omega_{jm}^{0c}\chi_c + \sum_{kc\in\mathcal{CN}} \Omega_{jm}^{kc}\lambda_{kc}.$$

- In matrix notation (Ω^0:Consumption; $\Omega^{\mathcal{NF}}$:IO for goods and factors):

$$\lambda' = \chi'\Omega^0 + \lambda'\Omega^{\mathcal{NF}}.$$

- Taking the differential:

$$d\lambda' = d\chi'\Omega^0\Psi^{\mathcal{NF}} + \chi' d\Omega^0\Psi^{\mathcal{NF}} + \chi'\Omega^0 d\Psi^{\mathcal{NF}}$$
$$= (d\chi'\Omega^0 + \chi' d\Omega^0 + \lambda' \, d\Omega^{\mathcal{NF}})\Psi^{\mathcal{NF}}.$$

Solving the model

- We can write everything in terms of $d \log w$ (last equality using Shephard's Lemma):

$$d \log \lambda_f = d \log w_f + d \log L_f \,, \qquad d\chi_c = \sum_{f \in \mathcal{F}_c} d\lambda_f \,, \qquad d \log p_{jm} = \sum_{f \in \mathcal{F}} \Psi_f^{jm} d \log w_f \,.$$

- Calculate differential exact hat-algebra by iterative means.

$$d \log w = A \, d \log w + B.$$

#	Equation	Matrix A	Vector B
1	$\sum_{jm\in\mathcal{N}} \sum_{c\in\mathcal{C}} \sum_{g\in\mathcal{F}} \lambda_g [d \log w_g + d \log L_g] b^c_{jm} \mathbb{1}_{g\in\mathcal{F}_c} \Psi^{jm}_f / \lambda_f$	$((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}})[b'((I_C \otimes 1'_F) \odot (\lambda^{\mathcal{F}})')]$	$A^{(1)} d \log L$
2	$\sum_{jm\in\mathcal{N}} \sum_{g\in\mathcal{F}} \sum_{c\in\mathcal{C}} \chi_c b^c_{jm} (1-\xi_j) \Psi^{jm}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}})(\Psi^{\mathcal{F}} \odot [1_C \otimes (1-\xi)] \odot [b'\chi])$	0_{CF}
3	$\sum_{jm\in\mathcal{N}} \sum_{c\in\mathcal{C}} \sum_{v\in\mathcal{C}} \sum_{g\in\mathcal{F}} \chi_c b^c_{jm} \left(\frac{\xi_j-\sigma}{bs_{cj}}\right) b^c_{jv} \Psi^{jv}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$\sum_{j\in\mathcal{I}} (\xi_j - \sigma)((\Psi^{\mathcal{F}}_{(j)})' \oslash \lambda^{\mathcal{F}})([\chi \odot b_{(j)} \oslash bs_{(j)}]' b_{(j)}) \Psi^{\mathcal{F}}_{(j)}$	0_{CF}
4	$\sum_{jm\in\mathcal{N}} \sum_{c\in\mathcal{C}} \sum_{iv\in\mathcal{N}} \sum_{g\in\mathcal{F}} \chi_c b^c_{jm} (\sigma-1) b^c_{iv} \Psi^{iv}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$(\sigma-1)((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}})(\chi \odot b)' b \Psi^{\mathcal{F}}$	0_{CF}
5	$\sum_{jm\in\mathcal{N}} \sum_{c\in\mathcal{C}} \chi_c b^c_{jm} \sigma \, d \log \omega^{0c}_j \Psi^{jm}_f / \lambda_f$	$0_{CF\times CF}$	$\sigma((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}}) \, [\chi'(b \odot d \log \omega)]'$
6	$\sum_{jm\in\mathcal{N}} \sum_{kc\in\mathcal{N}} \sum_{g\in\mathcal{F}} \lambda_{kc} \Omega^{kc}_{jm} (1-\xi_j) \Psi^{jm}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}})(\Psi^{\mathcal{F}} \odot [1_C \otimes (1-\xi)] \odot [(\Omega^{\mathcal{N}})' \lambda^{\mathcal{N}}])$	0_{CF}
7	$\sum_{jm\in\mathcal{N}} \sum_{v\in\mathcal{C}} \sum_{kc\in\mathcal{N}} \sum_{g\in\mathcal{F}} \lambda_{kc} \Omega^{kc}_{jm} \left(\frac{\xi_j-\varepsilon}{\Omega s^{kc}_j}\right) \Omega^{kc}_{jv} \Psi^{jv}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$\sum_{j\in\mathcal{I}} (\xi_j - \sigma)((\Psi^{\mathcal{F}}_{(j)})' \oslash \lambda^{\mathcal{F}})([\chi \odot \Omega^{\mathcal{N}}_{(j)} \oslash \Omega s_{(j)}]' \Omega^{\mathcal{N}}_{(j)}) \Psi^{\mathcal{F}}_{(j)}$	0_{CF}
8	$\sum_{jm\in\mathcal{N}} \sum_{kc\in\mathcal{N}} \sum_{iv\in\mathcal{N}} \sum_{g\in\mathcal{F}} \lambda_{kc} \Omega^{kc}_{jm} \left(\frac{\varepsilon-\phi}{1-\alpha_{kc}}\right) \Omega^{kc}_{iv} \Psi^{iv}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$(\varepsilon-\phi)((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}})([\lambda^{\mathcal{N}} \oslash (1-\alpha)] \odot \Omega^{\mathcal{N}})' \Omega^{\mathcal{N}} \Psi^{\mathcal{F}}$	0_{CF}
9	$\sum_{jm\in\mathcal{N}} \sum_{kc\in\mathcal{N}} \sum_{g\in\mathcal{F}} \lambda_{kc} \Omega^{kc}_{jm} \Psi^{kc}_g d \log w_g \Psi^{jm}_f / \lambda_f$	$(\phi-1)((\Psi^{\mathcal{F}})' \oslash \lambda^{\mathcal{F}})(\Omega^{\mathcal{N}} \odot \lambda^{\mathcal{N}})' \Psi^{\mathcal{F}}$	0_{CF}
10	$(\phi-1) \sum_{g\in\mathcal{F}} \Psi^{i_f}_g d \log w_g$	$(1-\phi)(I_{CF} - \Psi^{\mathcal{F}})$	0_{CF}
Ext	$\sum_g d\lambda_g = \sum_g \lambda_g (d \log w_g + d \log L_g) = 0$	$A_{1,1} = 0, \quad A_{1,g>1} = -\lambda_g$	$B_1 = -\log L' \cdot \lambda^{\mathcal{F}}$

Real Sector-Output and GDP

- Given the price change and the Domar weight change, the real sector-output change:

$$d \log y_{ic} = d \log \lambda_{ic} - d \log p_{ic}.$$

- Real GDP change from model primitives:
    - $\chi_c = \sum_{f \in \mathcal{F}_c} \lambda_f$
    - p_{0c}: Consumption price index

$$d \log \mathrm{GDP}_c = d \log \chi_c - d \log p_{0c}.$$

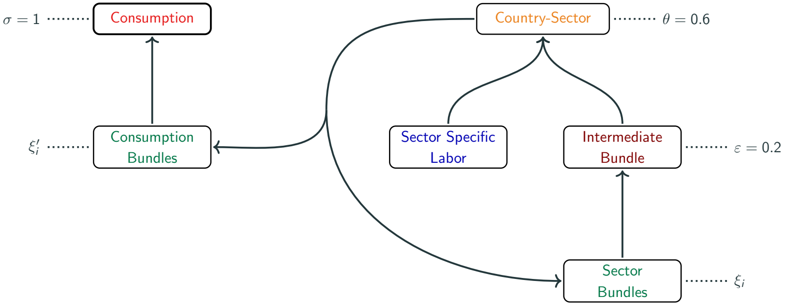
- To compare the post-pandemic real GDPs with the pre-pandemic levels, we use Tönrqvist price index—since this is 'chainable' (we integrate many small changes).

From Model to Data

Global Trade and Production Network: As of 2019

- OECD Inter-Country Input-Output (ICIO) Tables.
- 35 industries in 65 countries, giving us a matrix of 2275×2275 entries.
  - I-O structural links: input usages of industry i in country c from any industry in any country.
  - Expenditure shares (consumption)
  - Value-added (labor share)
- Employment by sector data from OECD's Trade in employment (TiM) database.

Elasticities



- Barrot and Sauvagnat (2016): Cobb-Douglas production breaks down in the SR (difficult to substitute among suppliers of same inputs).
- ε and ϕ are from Baqaee and Farhi (2022) Atalay (2017); Boehm et al. (2019)
- $\varepsilon = 0.2$—steel and plastic, $\phi = 0.6$—labor and inputs, $\xi_i = 0.2 - 1.5$—production input and consumption good trade (Caliendo & Parro (2015); Boehm et al. (2022)).

COVID shocks – Demand

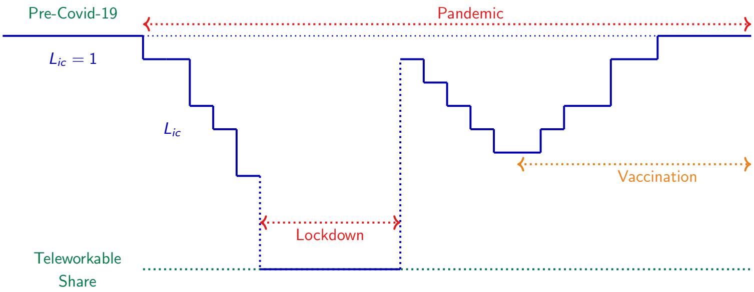
- Function of infection in country c: $I_{c,t}$
- Sectoral demand shifter (restaurants vs online grocery; gyms vs bicycles)

$$p_{0c} = \left[\sum_{j \in \mathcal{N}} \left(\delta_j^{0c}(I_{c,t}) \right)^{\sigma} \Omega s_j^{0c} \left(p_j^{0c} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} .$$

COVID shocks – Supply

- Function of infection in country c: $I_{c,t}$
- Sector specific shock to sector specific labor (factory workers vs accountants):

$$y_{ic} = \frac{A_{ic}}{\bar{A}_{ic}} \left[\alpha_{ic} \left(\frac{\Delta_{ic}(I_{c,t}) L_{ic}}{\bar{L}_{ic}} \right)^{\frac{1-\phi}{\phi}} + (1-\alpha_{ic}) \left(\frac{M_{ic}}{\bar{M}_{ic}} \right)^{\frac{1-\phi}{\phi}} \right]^{\frac{\phi}{1-\phi}} .$$



Estimating Sectoral-COVID shocks in Real Time

- Sectoral labor shortages and relative consumption changes: a combination of supply and demand factors and not observed in real time.

- Our approach (as of January 1, 2021): Use an epidemiological model to estimate sectoral supply and demand shocks—instrumentation with disease.

A Sectoral Epidemiological Model—Estimate Sectoral Labor Supply Shock

SIR Model – Basics

Population is divided in three categories:

- Susceptible (S_t)
- Infected (I_t)
- Recovered or Removed (R_t)
- Initial $I_{t=0}, S_{t=0}, R_{t=0}$ from data.

SIR Dynamics:

$$\begin{aligned}
\Delta S_t &= -\beta S_{t-1}\frac{I_{t-1}}{N} \\
\Delta R_t &= \gamma I_{t-1} \\
\Delta I_t &= \beta S_{t-1}\frac{I_{t-1}}{N} - \gamma I_{t-1}
\end{aligned}$$

Dynamics of pandemic is governed by:

$$R_0 \equiv \beta/\gamma$$

SIR with Sectoral Heterogeneity

- K sectors, indexed by $i = 1, \ldots, K$
- Non-working population: N_{NW}
- Industry i has L_i workers, some teleworkable (TW_i), some needs to be on-site (N_i) with:

$$L_i = TW_i + N_i$$

- Any given time, number of staying at home (will be denoted by subscript 0):

$$N_0 = N_{NW} + \sum_{i=1}^{K} TW_i.$$

SIR with Sectoral Heterogeneity

- Infection rate for at-home group is β_0.
- Industries have different physical proximity requirements, Prox_i.
- The rate of infection for each industry i, β_i:

$$\beta_i = \beta_0 \text{Prox}_i \qquad \text{for} \quad i = 1, \ldots, K$$

- Population weighted average of all βs (on-site workers can be infected at-home and on-site).

$$\beta_0 \frac{N_0}{N} + \sum_{i=1}^{K} (\beta_0 + \beta_i) \frac{N_i}{N} = \beta$$

$$\beta_0 = \beta \left(1 + \sum_{i=1}^{K} \frac{\text{Prox}_i N_i}{N} \right)^{-1}$$

2021: Evolution of Pandemic with Sectoral Heterogeneity

- $S_{i,t}$, $I_{i,t}$ and $R_{i,t}$: number of susceptible, infected and recovered individuals in sector i ($N_i = S_{i,t} + I_{i,t} + R_{i,t}$).
- Initial $I_{i,t=0} = \frac{N_i}{N} I_{t=0}, S_{i,t=0} = \frac{N_i}{N} S_{t=0}, R_{i,t=0} = \frac{N_i}{N} R_{t=0}$
- For at-home group:

$$\Delta S_{0,t} = -\beta_0 S_{0,t-1} \frac{I_{t-1}}{N}$$

- On-site workers in industry i, can be infected at work or with general public:

$$\Delta S_{i,t} = -\beta_i S_{i,t-1} \frac{I_{i,t-1}}{N_i} - \beta_0 S_{i,t-1} \frac{I_{t-1}}{N}$$

- Recovery rate is the same for all groups:

$$\Delta R_{i,t} = \gamma I_{i,t-1}$$

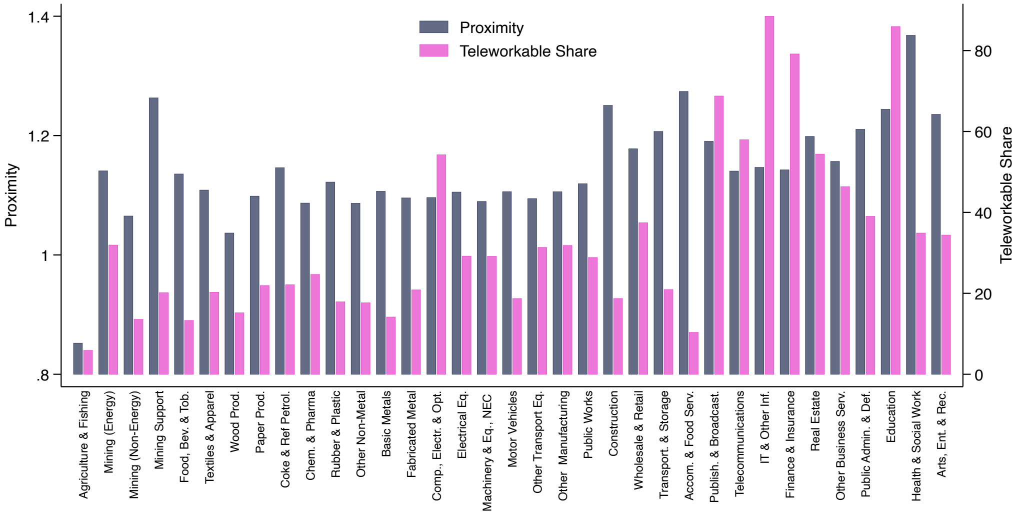
- Number of Infected in each group changes with:

$$\Delta I_{i,t} = -\left(\Delta R_{i,t} + \Delta S_{i,t}\right)$$

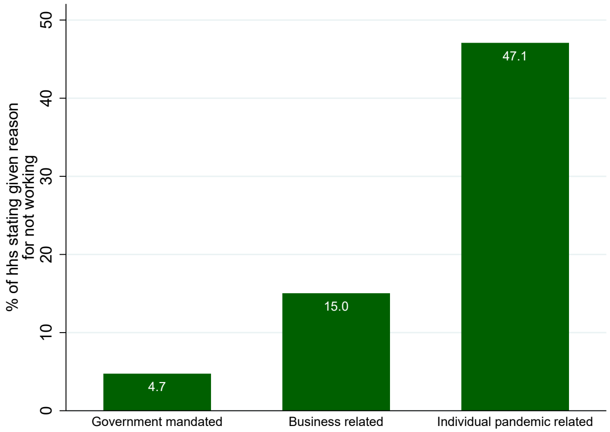
SIR Parameters w/Endogenous Lockdowns

- $\beta_{0,c}$, country specific-time varying infection rates are estimated from early 2020 until the end of 2020, Cakmakli and Simsek (2020).
- Use the values for December 2020 reflecting the stance of the pandemic at the onset of vaccines.
- Rate of recovery: $\gamma = 0.07 \Rightarrow$ 14 days for recovery.
- $R_{0,c} = \frac{\beta_{0,c}}{\gamma}$ for each country.
- Endogenous Lockdowns when ICU capacity is reached: 14 days of lockdowns with $\beta_c = 0$.
- Infection dynamics after lockdowns.

Sectoral Heterogeneity in COVID



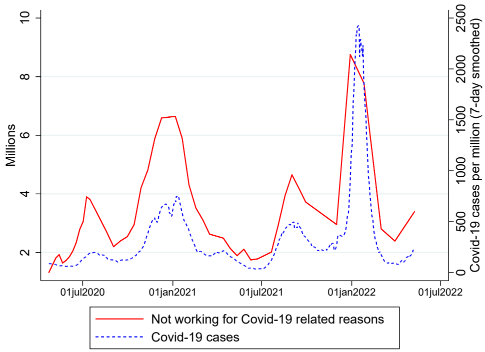
Sector labor supply shocks—US Census: Main Reasons for Not Working



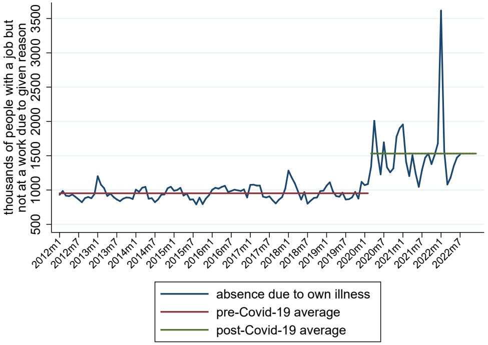
Fraction of population 18+ not working (excluding retired)

Pandemic ⇒ Labor supply shock

(a) Not working due to Covid-19



(b) Not working due to own illness over time



Data: Pulse Survey, US Census Bureau, Representative Sample

Sectoral Demand Shocks

- Use the US sectoral personal consumption from BEA.
- Regress sectoral consumption on the (log) number of infections over the course of 2021 to get δ_j^{0c}.
- Predict demand shocks to other countries using their infection rates and estimated δ_j^{0c}.
- Robustness: Sector specific credit card data from select countries

The Role of Global Trade and Production Network in Amplifying Losses from Sectoral Shocks

The Economic Case for Global Vaccinations

- Health shock is amplified via global I-0 network
- **Vaccination eliminates the labor supply shock and normalizes demand**

Scenario	AEs	EMDEs
I	Immediate Complete Vaccination	No Vaccination
II	Fast Vaccination	Slow Vaccination

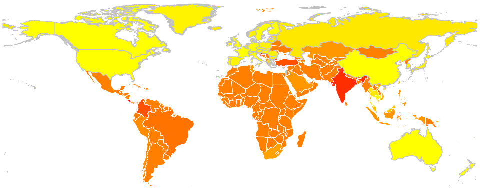
GDP Decline Relative to Pre-Pandemic under Counterfactual Scenario

Scenario I

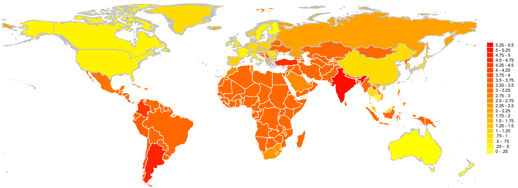
Consumption & Production Trade Elasticities		**World**	**AE**	**EMDE**	**Share of AEs (%)**
(1)	ξ_i', ξ_i =0.50	2.149	0.561	1.588	26.1
(2)	ξ_i', ξ_i =0.60	1.347	0.312	1.035	23.2
(3)	ξ_i', ξ_i =0.70	0.996	0.189	0.806	19.0
(4)	ξ_i', ξ_i =0.80	0.898	0.140	0.758	15.6
(5)	ξ_i', ξ_i =0.90	0.857	0.112	0.744	13.1

Country Heterogeneity under Counterfactual Scenario by Trade Elasticity

(a) $\xi_i = 0.9$



(b) $\xi_i = 0.6$

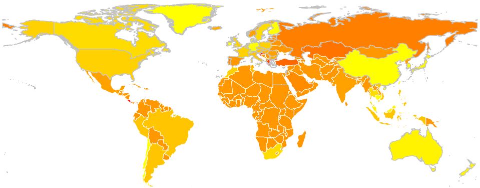


GDP Decline Relative to Pre-Pandemic under Scenario II

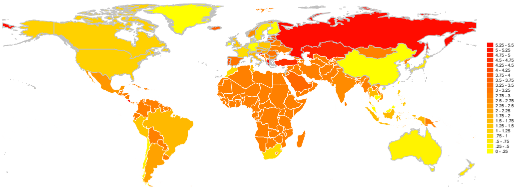
	Consumption & Production Trade Elasticities	Scenario II World	AE	EMDE	Share of AEs (%)
(1)	$\xi_i', \xi_i = 0.50$	2.687	1.038	1.649	38.6
(2)	$\xi_i', \xi_i = 0.60$ (Baseline)	1.296	0.592	0.705	45.6
(3)	$\xi_i', \xi_i = 0.70$	1.125	0.560	0.565	49.8
(4)	$\xi_i', \xi_i = 0.80$	1.072	0.550	0.523	51.2
(5)	$\xi_i', \xi_i = 0.90$	1.049	0.545	0.504	51.9
(6)	Caliendo and Parro (2015)	1.018	0.523	0.495	51.4

Country Heterogeneity under Scenario II by Trade Elasticity

(a) $\xi_i = 0.9$



(b) $\xi_i = 0.6$



Robustness

- Remove demand shocks (AE share 44)
- Remove international linkages (AE share 53)
- Cobb-Douglas vs Leontief-like production (AE share 53 vs 48)
- No endogenous lockdowns (AE share 21)

Conclusion

- There is an economic case for global vaccinations on top of the moral case; loss to rich country GDP is larger than the investment needed for global vaccinations (a return of $200\times$)

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Conclusion

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- Losses to rich world in the range of 0.1 to 1 percent of 2019 world GDP depending on the degree of complementarity across factors of production (mostly trade elasticises for input trade)
- Supply chain disruptions can stay under sectoral supply shocks combined with stimulative policies

Conclusion

- There is an economic case for global vaccinations on top of the moral case; loss to rich country GDP is larger than the investment needed for global vaccinations (a return of $200\times$)
- Losses to rich world in the range of 0.1 to 1 percent of 2019 world GDP depending on the degree of complementarity across factors of production (mostly trade elasticises for input trade)
- Supply chain disruptions can stay under sectoral supply shocks combined with stimulative policies
- Given the extent of globalization, no economy fully recovers until every economy recovers, and hence a multilateral approach is a "must."

Appendix

The Role of Production Elasticities

Consumption & Production Trade Elasticities		**Scenario II** World	AE	EMDE	Share of AEs (%)
Baseline	$\xi_i' = 0.6, \xi_i = 0.6$	1.296	0.592	0.705	45.6
(1)	$\xi_i' = 1.1, \xi_i = 0.5$	1.607	0.726	0.881	45.2
(2)	$\xi_i' = 1.1, \xi_i = 0.6$	1.151	0.585	0.566	50.8
(3)	$\xi_i' = 1.1, \xi_i = 0.9$	1.039	0.541	0.498	52.1

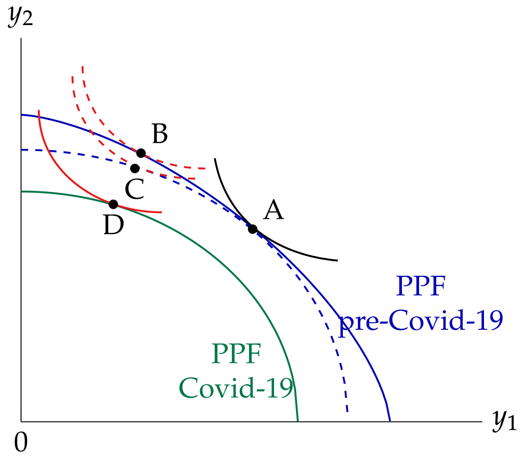
The Role of Production and Consumption Elasticities

		Scenario II			
	Elasticities	**World**	**AE**	**EMDE**	**Share of AEs (%)**
Baseline	$\xi'_i, \xi_i = 0.60$	1.296	0.592	0.705	45.6
(1)	$\xi'_i, \xi_i = 0.60$, $\sigma = 1.5$	1.387	0.658	0.730	47.4
(2)	$\xi'_i, \xi_i = 0.60$, $\sigma = 0.5$	1.555	0.589	0.966	37.9
(3)	$\xi'_i, \xi_i = 0.60$, $\theta = 1.5$	0.928	0.469	0.460	50.5
(4)	$\xi'_i, \xi_i = 0.60$, $\varepsilon = 0.5$	1.131	0.552	0.580	48.7
(5)	$\xi'_i, \xi_i = 0.60$, $\varepsilon = 1.5$	0.411	0.233	0.177	56.8
(6)	Cobb-Douglas	0.818	0.441	0.377	53.9
(7)	Leontief-like	3.448	1.675	1.773	48.6

The Role of International Linkages and Demand Shocks

	Scenario II			
	World	**AE**	**EMDE**	**Share of AEs (%)**
Baseline	1.296	0.592	0.705	45.6
(1) No IPN	1.045	0.556	0.490	53.2
(2) No DS	0.892	0.398	0.495	44.5

Sectoral Shocks and Production Possibility Frontier



- **A**: Equilibrium pre-Covid
- **B**: Equilibrium with sectoral demand shock
- **C**: Equilibrium with sectoral demand shock + sector-specific labor
- **D**: Equilibrium with sectoral demand shock + sector-specific labor + sectoral labor shock

GDP Decline Relative to the Pre-Pandemic World (percent): No Endogenous Lockdowns

		Baseline Scenarios			
	Parameter Setup	**World**	**AE**	**EMDE**	**Share of AEs (%)**
(1)	$\xi_i', \xi_i =$0.60 (With lockdown)	1.296	0.592	0.705	45.6
(2)	$\xi_i', \xi_i =$0.60 (Without Lockdown)	0.757	0.159	0.598	21.0