ONLINE APPENDIX TO
International Comovement in the Global Production Network*

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A. Data Description

Tables A1 and A2 list the sectors and countries in our analysis. Figure A1 illustrates the average imported input intensity by sector in our data. Figure A2 displays two heat maps for the G7 countries. In each, both rows and columns are broken into country-sectors, though due to space constraints sectors are too numerous to be labeled. On the left is the usual heat map of log intermediate input shares in the WIOD, with the suppliers on the x-axis, and input users on the y-axis. Versions of this heat map have appeared in the literature (see, e.g., Jones, 2013). The most saturated reds, indicating greater input linkages, are in blocks on the diagonal, corresponding to countries' domestic linkages. On the right is the heat map of log final expenditure shares instead. For final shares, there is no notion of a using (y-axis) sector, as final expenditure is undertaken by a representative consumer in each country. Nonetheless, we keep the format of the plot the same. Once again, domestic final shares are the highest, but there is meaningful variation across sectors within country pairs. Both intermediate and final shares are inputs into the influence matrix.

Table A1: Sectors

agriculture hunting forestry and fishing	basic metals and fabricated metal
financial intermediation	mining and quarrying
machinery nec	real estate activities
food beverages and tobacco	electrical and optical equipment
renting of m&eq and other business activities	textiles textile leather and footwear
transport equipment	public admin and defense; compulsory social security
wood and of wood and cork	manufacturing nec; recycling
education	pulp paper paper printing and publishing
electricity gas and water supply	health and social work
coke refined petroleum and nuclear fuel	construction
other community social and personal services	chemicals and chemical products
hotels and restaurants	sale maintenance and repair of motor vehicles
rubber and plastics	transport and storage
wholesale trade and commission trade	other nonmetallic mineral
post and telecommunications	retail trade except of motor vehicles

Table A2: Country Sample

G7	Rest			
Canada	Australia	Finland	Lithuania	Spain
France	Austria	Greece	Netherlands	Sweden
Germany	Belgium	Hungary	Poland	
Italy	Cyprus	India	Portugal	
Japan	Czech Republic	Ireland	Russian Federation	
UK	Denmark	Republic of Korea	Slovak Republic	
USA	Estonia	Latvia	Slovenia	

Figure A1: Average Sectoral Imported Input Intensity

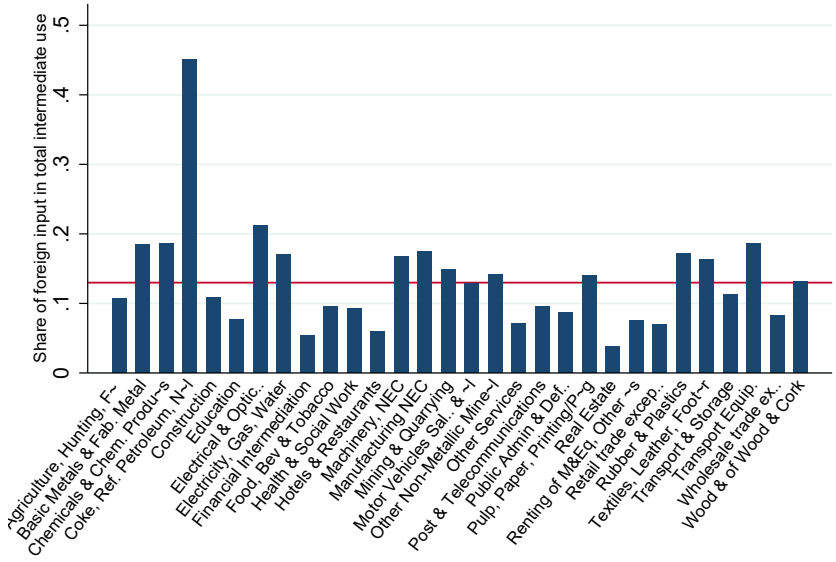
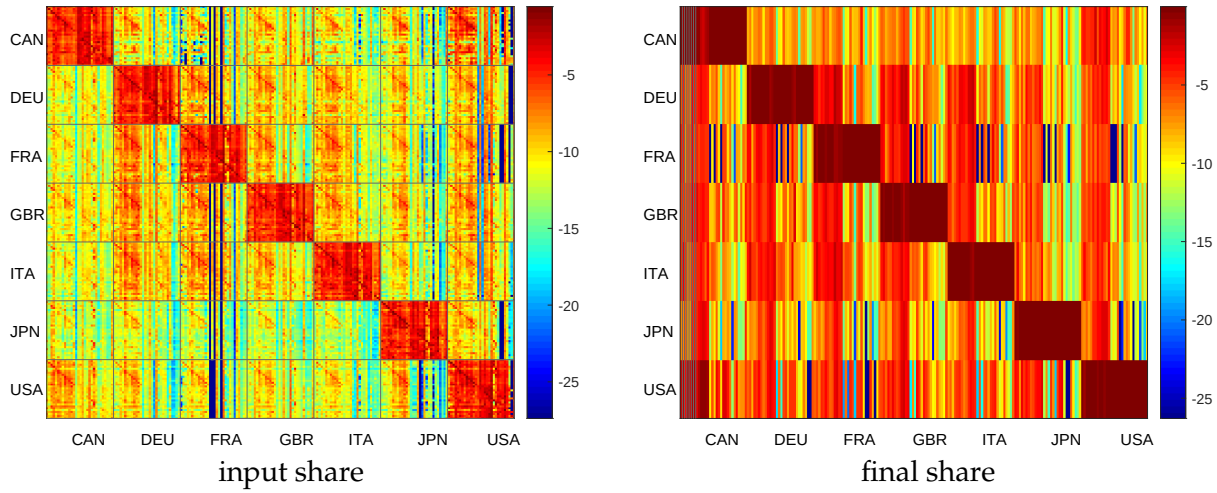


Figure A2: Input and Final Use Heat Maps, G7



Notes: This figure displays the heat maps of the log intermediate input shares in WIOD (left) and the log final spending shares (right) for the G7 countries.

B. Model and Quantitative Results

Throughout this appendix, variables without a t-subscript denote steady-state values, and variables with a t-subscript denote their realizations following a shock.

B.1 Proofs

Proof of Proposition 3.1. The market clearing condition for the sales in country n sector j in levels is

$$P_{nj,t}Y_{nj,t} = \sum_m P_{m,t}\mathcal{F}_{m,t}\pi^f_{nmj,t} + \sum_m \sum_i (1-\eta_i)P_{mi,t}Y_{mi,t}\pi^x_{nj,mi,t}.$$

Note that with financial autarky, the total sales of final goods is the same as the value added across sectors

$$P_{m,t}\mathcal{F}_{m,t} = \sum_i \eta_i P_{mi,t}Y_{mi,t}.$$

The market clearing condition is then

$$P_{nj,t}Y_{nj,t} = \sum_m \sum_i \eta_i P_{mi,t}Y_{mi,t}\pi^f_{nmj,t} + \sum_m \sum_i (1-\eta_i)P_{mi,t}Y_{mi,t}\pi^x_{nj,mi,t}.$$

Log-linearizing:

$$\begin{aligned}\ln P_{nj,t} + \ln Y_{nj,t} = &\sum_m \sum_i \frac{\pi^f_{nmj}P_m\mathcal{F}_m}{P_{nj}Y_{nj}} \frac{\eta_i P_{mi}Y_{mi}}{P_m\mathcal{F}_m}\left(\ln P_{mi,t} + \ln Y_{mi,t} + \ln \pi^f_{nmj,t}\right) \\ &+ \sum_m \sum_i \frac{(1-\eta_i)\pi^x_{nj,mi}P_{mi}Y_{mi}}{P_{nj}Y_{nj}}(\ln P_{mi,t} + \ln Y_{mi,t} + \ln \pi^x_{nj,mi,t}) \end{aligned} \tag{B.1}$$

and the log-deviation of import shares are given by

$$\begin{aligned}\ln \pi^f_{nmj,t} =&(1-\rho)\sum_k \pi^c_{kmj}\left(\ln P_{nj,t} - \ln P_{kj,t}\right) \\ \ln \pi^x_{nj,mi,t} =&(1-\varepsilon)\sum_{k,\ell} \pi^x_{kl,mi}\left(\ln P_{nj,t} - \ln P_{k\ell,t}\right).\end{aligned}$$

Define the following share matrices:

1. $\mathbf{\Psi}^f$ is an $NJ \times N$ matrix whose (nj, m)th element is $\frac{\pi^f_{nmj}P_m\mathcal{F}_m}{P_{nj}Y_{nj}}$. That is, this matrix stores the share of total revenue in the country-sector in the row that comes from final spending in the country in the column.

2. $\mathbf{\Psi}^x$ is an $NJ \times NJ$ matrix whose (nj, mi)th element is $\frac{(1-\eta_i)\pi^x_{nj,mi}P_{mi}Y_{mi}}{P_{nj}Y_{nj}}$. That is, this matrix stores the share of total revenue in the country-sector in the row that comes from intermediate spending in the country-sector in the column.

3. $\mathbf{\Upsilon}$ is an $N \times NJ$ matrix whose (n, mi)th element is $\frac{\eta_i P_{mi}Y_{mi}}{P_n\mathcal{F}_n}$. That is, this matrix stores the share of value added in the country-sector in the column in total GDP of the country in the row. Note that the elements are zero whenever $m \neq n$.

4. $\mathbf{\Pi}^f$ is an $NJ \times NJ$ matrix whose $(mi, k\ell)$th element is $\pi^f_{km\ell}$. That is, this matrix stores the final expenditure share in the country in the row from the goods coming from the country-sector in the column. The elements for different sectors in the row within the same country country are identical.

5. $\mathbf{\Pi}^c$ is an $N \times NJ$ matrix whose $(m, k\ell)$th element is $\pi^c_{km\ell}$. That is, this matrix stores the final expenditure share in the country in the row from the goods coming from the country-sector in the column. This share is within the goods in the sector in the column.

6. $\mathbf{\Pi}^x$ is an $NJ \times NJ$ matrix whose $(k\ell, mi)$th element is $\pi^x_{mi,k\ell}$. That is, this matrix stores the intermediate expenditure share on goods coming from the column in the country-sector in the row.

Then, equation (B.1) can be stated in matrix form:

$$\begin{aligned}\ln \mathbf{P}_t + \ln \mathbf{Y}_t =& \left(\mathbf{\Psi}^f \mathbf{\Upsilon} + \mathbf{\Psi}^x\right)(\ln \mathbf{P}_t + \ln \mathbf{Y}_t) + (1-\rho)\left(\operatorname{diag}\left(\mathbf{\Psi}^f \mathbf{1}\right) - \mathbf{\Psi}^f \mathbf{\Pi}^c\right) \ln \mathbf{P}_t \\ &+ (1-\varepsilon)\left(\operatorname{diag}\left(\mathbf{\Psi}^x \mathbf{1}\right) - \mathbf{\Psi}^x \mathbf{\Pi}^x\right) \ln \mathbf{P}_t.\end{aligned}$$

This allows us to express prices as a function of quantities

$$\ln P_t = \mathcal{P} \ln Y_t, \tag{B.2}$$

where[1]

$$\begin{aligned}\mathcal{P} &= -\left(\mathbf{I} - \mathcal{M}\right)^+ \left(\mathbf{I} - \mathbf{\Psi}^f \mathbf{\Upsilon} - \mathbf{\Psi}^x\right) \\ \mathcal{M} &= \mathbf{\Psi}^f \mathbf{\Upsilon} + \mathbf{\Psi}^x + (1-\rho)\left(\operatorname{diag}\left(\mathbf{\Psi}^f \mathbf{1}\right) - \mathbf{\Psi}^f \mathbf{\Pi}^f\right) + (1-\varepsilon)\left(\operatorname{diag}\left(\mathbf{\Psi}^x \mathbf{1}\right) - \mathbf{\Psi}^x \mathbf{\Pi}^x\right).\end{aligned}$$

Turning to the supply side, the labor demand (3.8) stacked into an $NJ \times 1$ vector is:

$$\ln \mathbf{W}_t - \ln \mathbf{P}_t = \ln \mathbf{Y}_t - \ln \mathbf{H}_t.$$

The log-linearized version of the final goods price in country n is

$$\ln P_{n,t} = \sum_j \nu_{nj} \sum_m \pi^c_{mnj} \ln P_{mj,t} = \sum_{m,j} \pi^f_{mnj} \ln P_{mj,t}.$$

The labor supply in vector notation is:

$$\ln \mathbf{H}_t = \psi(\ln \mathbf{W}_t - \ln \mathbf{P}^f_t),$$

where $\ln \mathbf{P}^f_t$ denotes the consumption price index (3.4) that prevails at each sector in log-deviations and matrix notation:

$$\ln \mathbf{P}^f_t = \mathbf{\Pi}^f \ln \mathbf{P}_t. \tag{B.3}$$

[1] The + sign stands for the Moore-Penrose inverse as $\mathbf{I} - \mathcal{M}$ is not invertible. The non-invertibility is a consequence of the fact that the vector of prices is only defined up to a numeraire.

These three conditions imply the following equilibrium relationship for hours:

$$\ln \mathbf{H}_t = \frac{\psi}{1+\psi} \ln \mathbf{Y}_t + \frac{\psi}{1+\psi} \left(\mathbf{I} - \mathbf{\Pi}^f \right) \ln \mathbf{P}_t. \tag{B.4}$$

Similarly, market clearing for intermediate inputs is:

$$\ln \mathbf{P}_t^x - \ln \mathbf{P}_t = \ln \mathbf{Y}_t - \ln \mathbf{X}_t,$$

where $\ln \mathbf{P}_t^x$ is the vector of intermediate input price indices for all countries and sectors:

$$\ln \mathbf{P}_t^x \quad = \quad \mathbf{\Pi}^x \ln \mathbf{P}_t.$$

Jointly, these imply

$$\ln \mathbf{X}_t = \ln \mathbf{Y}_t + (\mathbf{I} - \mathbf{\Pi}^x) \ln \mathbf{P}_t.$$

Plugging these into the production function

$$\begin{aligned}
\ln \mathbf{Y}_t &= \ln \mathbf{Z}_t + \boldsymbol{\eta}\boldsymbol{\alpha} \ln \mathbf{H}_t + \boldsymbol{\eta}(\mathbf{I} - \boldsymbol{\alpha}) \ln \mathbf{K}_t + (\mathbf{I} - \boldsymbol{\eta}) \ln \mathbf{X}_t. \\
&= \ln \mathbf{Z}_t + \boldsymbol{\eta}(\mathbf{I} - \boldsymbol{\alpha}) \ln \mathbf{K}_t + \boldsymbol{\eta}\boldsymbol{\alpha} \left(\frac{\psi}{1+\psi} \ln \mathbf{Y} + \frac{\psi}{1+\psi} \left(\mathbf{I} - \mathbf{\Pi}^f \right) \ln \mathbf{P}_t \right) + (\mathbf{I} - \boldsymbol{\eta}) \left(\ln \mathbf{Y}_t + (\mathbf{I} - \mathbf{\Pi}^x) \ln \mathbf{P}_t \right). \\
&= \ln \mathbf{Z}_t + \boldsymbol{\eta}(\mathbf{I} - \boldsymbol{\alpha}) \ln \mathbf{K}_t + \left[\frac{\psi}{1+\psi} \boldsymbol{\eta}\boldsymbol{\alpha} \left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f \right) \boldsymbol{\mathcal{P}} \right) + (\mathbf{I} - \boldsymbol{\eta}) \left(\mathbf{I} + (\mathbf{I} - \mathbf{\Pi}^x) \boldsymbol{\mathcal{P}} \right) \right] \ln \mathbf{Y}_t,
\end{aligned}$$

where in the last step we use (3.16) for $\ln \mathbf{P}_t$. Inverting for $\ln \mathbf{Y}_t$ completes the proof:

$$\ln \mathbf{Y}_t = \left(\mathbf{I} - \frac{\psi}{1+\psi} \boldsymbol{\eta}\boldsymbol{\alpha} \left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f \right) \boldsymbol{\mathcal{P}} \right) - (\mathbf{I} - \boldsymbol{\eta}) \left(\mathbf{I} + (\mathbf{I} - \mathbf{\Pi}^x) \boldsymbol{\mathcal{P}} \right) \right)^{-1} \left(\ln \mathbf{Z}_t + \boldsymbol{\eta}(\mathbf{I} - \boldsymbol{\alpha}) \ln \mathbf{K}_t \right). \tag{B.5}$$

Proof of Proposition 3.2. The log-deviation of country n's real GDP from steady state can be expressed as

$$\begin{aligned}
\ln G_{n,t} &= \sum_j \left(\frac{P_{nj} Y_{nj}}{G_n} \ln Y_{nj,t} - \frac{P_{nj}^x X_{nj}}{G_n} \ln X_{nj,t} \right) \\
&= \sum_j \frac{P_{nj} Y_{nj}}{G_n} \left(\ln Y_{nj,t} - \frac{P_{nj}^x X_{nj}}{P_{nj} Y_{nj}} \ln X_{nj,t} \right) \\
&= \sum_j \frac{P_{nj} Y_{nj}}{G_n} \left(\ln Z_{nj,t} + \eta_j \alpha_j \ln H_{nj,t} + \eta_j (1 - \alpha_j) \ln K_{nj,t} + (1 - \eta_j) \ln X_{nj,t} - \frac{P_{nj}^x X_{nj}}{P_{nj} Y_{nj}} \ln X_{nj,t} \right),
\end{aligned}$$

which leads directly to (3.17), since in equilibrium $\frac{P_{nj}^x X_{nj}}{P_{nj} Y_{nj}} = (1 - \eta_j)$.

The derivation of (3.18) plugs (3.16) and (3.13)-(3.14) into (B.4), which leads to

$$\ln \mathbf{H}_t \equiv \boldsymbol{\mathcal{H}} \left(\ln \mathbf{Z}_t + (\boldsymbol{\eta} - \boldsymbol{\alpha}\boldsymbol{\eta}) \ln \mathbf{K}_t \right), \quad \boldsymbol{\mathcal{H}} = \frac{\psi}{1+\psi} \left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f \right) \boldsymbol{\mathcal{P}} \right) \mathbf{\Lambda}. \tag{B.6}$$

Proof of Corollary 3.3. With $\rho = \varepsilon = 1$, the market clearing condition reduces to

$$\ln \mathbf{P}_t + \ln \mathbf{Y}_t = \left(\mathbf{\Psi}^f \mathbf{\Upsilon} + \mathbf{\Psi}^x\right)(\ln \mathbf{P}_t + \ln \mathbf{Y}_t),$$

which implies that

$$\ln \mathbf{P}_t = -\ln \mathbf{Y}_t, \qquad \mathcal{P} = -\mathbf{I}.$$

As a result, the influence matrix simplifies to

$$\ln \mathbf{Y}_t = \left(\mathbf{I} - \frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\mathbf{\Pi}^f - (\mathbf{I} - \boldsymbol{\eta})\mathbf{\Pi}^x\right)^{-1} (\ln \mathbf{Z}_t + \boldsymbol{\eta}(\mathbf{I} - \boldsymbol{\alpha}) \ln \mathbf{K}_t)\,. \tag{B.7}$$

The hours influence matrix is:

$$\mathcal{H} = \frac{\psi}{1+\psi}\left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f\right)\mathcal{P}\right)\mathbf{\Lambda} = \frac{\psi}{1+\psi}\mathbf{\Pi}^f \left(\mathbf{I} - \frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\mathbf{\Pi}^f - (\mathbf{I} - \boldsymbol{\eta})\mathbf{\Pi}^x\right)^{-1}.$$

By construction, each row of $\mathbf{\Pi}^f$ and $\mathbf{\Pi}^x$ sum to one. Therefore, the largest eigenvalue of $\mathbf{\Pi}^f$ and $\mathbf{\Pi}^x$ equals to 1. Also note that both $\boldsymbol{\alpha}$ and $\boldsymbol{\eta}$ are diagonal matrix with elements less than 1. It follows that the largest eigenvalue of $\frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\mathbf{\Pi}^f + (\mathbf{I} - \boldsymbol{\eta})\mathbf{\Pi}^x$ is bounded from above by $\frac{\psi}{1+\psi}$ which is less than 1. It follows that $\mathcal{H}$ admits the following expansion

$$\mathcal{H} = \frac{\psi}{1+\psi}\mathbf{\Pi}^f \sum_{k=0}^{\infty} \left(\frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\mathbf{\Pi}^f + (\mathbf{I} - \boldsymbol{\eta})\mathbf{\Pi}^x\right)^k.$$

Proof of Proposition 3.4. In steady state, the intertemporal Euler condition can be written as

$$1 = \beta\left(\eta_j \alpha_j \frac{P_{nj} Y_{nj}}{P_n K_{nj}} + 1 - \delta_j\right).$$

Meanwhile, the budget constraint in the steady state is

$$P_n C_n + P_n \sum_j \delta_j K_{nj} = \sum_j \eta_j P_{nj} Y_{nj}.$$

These conditions imply that the steady state investment-to-output and consumption-to-output ratios can be expressed as

$$\begin{aligned}
\frac{\delta_j K_{nj}}{G_n} &= \eta_j \alpha_j \omega_{nj} \frac{\delta_j}{\beta^{-1} - 1 + \delta_j}, \\
\frac{C_n}{G_n} &= \sum_j \eta_j \omega_{nj} \left(1 - \frac{\alpha_j \delta_j}{\beta^{-1} - 1 + \delta_j}\right),
\end{aligned}$$

where G_n is GDP in country n and ω_{nj} is the Domar weight.

The steady state intratemporal Euler condition is

$$H_{nj}^{1+\frac{1}{\psi}} = \eta_j (1 - \alpha_j) \frac{P_{nj} Y_{nj}}{P_n},$$

which implies that

$$\frac{1}{G_n}\frac{H_{nj}^{1+\frac{1}{\psi}}}{1+\frac{1}{\psi}} = \frac{\psi}{1+\psi}\eta_j(1-\alpha_j)\omega_{nj}.$$

Now turn to the linearized version of the model. Starting from the budget constraint, we have

$$\frac{C_n}{G_n}\ln C_{n,t} + \sum_j \frac{\delta_j K_{nj}}{G_n}\ln I_{nj,t} = \sum_j \eta_j\omega_{nj}(\ln P_{nj,t} - \ln P_{n,t} + \ln Y_{nj,t})$$

Using the law of motion for capital accumulation, the changes in investment are given by

$$\ln I_{nj,t} = \frac{\ln K_{nj,t+1} - (1-\delta_j)\ln K_{nj,t}}{\delta_j}.$$

Therefore, the change of consumption can be written in terms of $\ln \mathbf{Y}_t$, $\ln K_{nj,t}$, and $\ln K_{nj,t+1}$, as changes in prices can be expressed as a function of $\ln \mathbf{Y}_t$

$$\frac{C_n}{G_n}\ln C_{n,t} = \sum_j \eta_j\omega_{nj}(\ln P_{nj,t} - \ln P_{n,t} + \ln Y_{nj,t}) - \sum_j \frac{\delta_j K_{nj}}{G_n}\left(\frac{\ln K_{nj,t+1} - (1-\delta_j)\ln K_{nj,t}}{\delta_j}\right). \tag{B.8}$$

Let ϕ_{nt} denote the deviation of the marginal utility of consumption

$$\phi_{n,t} = \left(C_{n,t} - \sum_j \frac{H_{nj,t}^{1+\frac{1}{\psi}}}{1+\frac{1}{\psi}}\right)^{-\sigma}$$

Utilizing the steady-state properties of consumption and hours, it follows that its linearized version is

$$\ln\phi_{n,t} \equiv -\sigma\left(\frac{C_n\ln C_{n,t} - \sum_j \frac{H_{nj}^{1+\frac{1}{\psi}}}{1+\frac{1}{\psi}}\left(1+\frac{1}{\psi}\right)\ln H_{nj,t}}{C_n - \sum_j \frac{H_{nj}^{1+\frac{1}{\psi}}}{1+\frac{1}{\psi}}}\right) = -\sigma\frac{\sum_j \eta_j\omega_{nj}\left(\left(1-\frac{\alpha_j\delta_j}{\beta^{-1}-1+\delta_j}\right)\ln C_{n,t} - (1-\alpha_j)\ln H_{nj,t}\right)}{\sum_j \eta_j\omega_{nj}\left(1-\frac{\alpha_j\delta_j}{\beta^{-1}-1+\delta_j} - \frac{\psi}{1+\psi}(1-\alpha_j)\right)}$$

The linearized Euler equation is

$$\ln\phi_{n,t} = \mathbb{E}_t\left[\phi_{n,t+1} + (1-\beta+\beta\delta_j)(\ln P_{nj,t+1} - \ln P_{n,t+1} + \ln Y_{nj,t+1} - \ln K_{nj,t+1})\right]. \tag{B.9}$$

Combining condition (B.2), (B.3), (B.5), (B.6), and (B.8) with condition (B.9), it boils down to a second-order difference system involving only $\ln \mathbf{K}_t$, $\ln \mathbf{K}_{t+1}$, $\ln \mathbf{K}_{t+2}$, $\ln \mathbf{Z}_t$, and $\ln \mathbf{Z}_{t+1}$

$$\mathbf{D}_0\ln\mathbf{K}_t + \mathbf{D}_1\ln\mathbf{K}_{t+1} + \mathbf{D}_2\mathbb{E}[\ln\mathbf{K}_{t+2}] + \mathbf{F}_1\ln\mathbf{Z}_t + \mathbf{F}_2\mathbb{E}[\ln\mathbf{Z}_{t+1}] = \mathbf{0}, \tag{B.10}$$

where the matrices $\mathbf{D}_0, \mathbf{D}_1, \mathbf{D}_2, \mathbf{F}_1, \mathbf{F}_2$ are functions of the parameters and the steady-state input and output shares.

We proceed by the method of undetermined coefficients. Suppose that

$$\ln \mathbf{K}_{t+1} = \mathbf{M} \ln \mathbf{K}_t + \mathbf{\Gamma} \ln \mathbf{Z}_t. \tag{B.11}$$

We assume that the TFP shock obeys the following autoregressive process,

$$\ln \mathbf{Z}_t = \boldsymbol{\varrho} \ln \mathbf{Z}_{t-1} + \boldsymbol{\theta}_t, \tag{B.12}$$

where $\boldsymbol{\varrho}$ governs the persistence of the system and $\boldsymbol{\theta}_t$ are a vector of innovations that are serially uncorrelated.

Plugging equations (B.11) and (B.12) into (B.10) leads to

$$\mathbf{D}_0 \ln \mathbf{K}_t + \mathbf{D}_1(\mathbf{M} \ln \mathbf{K}_t + \mathbf{\Gamma} \ln \mathbf{Z}_t) + \mathbf{D}_2(\mathbf{M}(\mathbf{M} \ln \mathbf{K}_t + \mathbf{\Gamma} \ln \mathbf{Z}_t) + \mathbf{\Gamma} \boldsymbol{\varrho} \ln \mathbf{Z}_t) + \mathbf{F}_1 \ln \mathbf{Z}_t + \mathbf{F}_2 \boldsymbol{\varrho} \ln \mathbf{Z}_t = \mathbf{0}.$$

This condition above needs to hold for all possible realization of $\ln \mathbf{K}_t$ and $\ln \mathbf{Z}_t$. The resulting fixed-point problem is

$$\mathbf{D}_0 + \mathbf{D}_1 \mathbf{M} + \mathbf{D}_2 \mathbf{M}^2 = 0 \tag{B.13}$$

$$(\mathbf{D}_1 + \mathbf{D}_2 \mathbf{M}) \mathbf{\Gamma} + \mathbf{D}_2 \mathbf{\Gamma} \boldsymbol{\varrho} + \mathbf{F}_1 + \mathbf{F}_2 \boldsymbol{\varrho} = 0. \tag{B.14}$$

Note that $\mathbf{M}$ can be solved separately using only condition (B.13). The solution to this second-order equation in matrix form needs to satisfy the condition that all the eigenvalues of $\mathbf{M}$ have to be less than 1 in norm. Once $\mathbf{M}$ is obtained, $\mathbf{\Gamma}$ can be solved using condition (B.14).

Rearranging the policy function (B.11) gives

$$\ln \mathbf{K}_{t+1} = \mathbf{M} \mathbb{L} \ln \mathbf{K}_t + \mathbf{\Gamma} \ln \mathbf{Z}_t = (\mathbf{I} - \mathbf{M} \mathbb{L})^{-1} \mathbf{\Gamma} \ln \mathbf{Z}_t.$$

Proof of Proposition 3.5. Under full depreciation, we use a guess-and-verify approach to show that the saving rate is constant in each country. Suppose the consumption rate in country n is $1 - \chi$, then

$$C_{n,t} = \frac{1}{P_{n,t}} (1 - \chi) \sum_j \eta_j P_{nj,t} Y_{nj,t}.$$

Meanwhile, the intratemporal Euler equation implies that

$$H_{nj,t}^{\frac{1}{\psi}} = \frac{1}{P_{n,t}} \frac{\psi}{1 + \psi} \alpha \eta_j P_{nj,t} Y_{nj,t},$$

where we have invoked the assumption that $\alpha_j = \alpha$. When $U(\cdot) = \ln(\cdot)$, that the marginal utility of consumption is

$$\phi_{n,t} = \frac{1}{C_{n,t} - \sum_j H_{nj,t}^{1 + \frac{1}{\psi}}} = \frac{P_{n,t}}{(1 - \chi) \sum_j \eta_j P_{nj,t} Y_{nj,t} - \frac{\psi}{1+\psi} \alpha \sum_j \eta_j P_{nj,t} Y_{nj,t}}$$

The Euler condition requires that

$$\phi_{n,t} = \beta \mathbb{E}_t \left[\phi_{n,t+1} \left(\frac{R_{nj,t+1}}{P_{n,t+1}} \right) \right].$$

Using the equilibrium condition that $K_{nj,t}R_{nj,t} = (1-\alpha)\eta_j P_{nj,t}Y_{nj,t}$, the Euler equation becomes

$$\frac{P_{n,t}K_{nj,t+1}}{(1-\chi)\sum_j \eta_j P_{nj,t}Y_{nj,t} - \frac{\psi}{1+\psi}\sum_j \alpha\eta_j P_{nj,t}Y_{nj,t}} = \beta\mathbb{E}\left[\frac{(1-\alpha)\eta_j P_{nj,t+1}Y_{nj,t+1}}{(1-\chi)\sum_j \eta_j P_{nj+1t}Y_{nj,t+1} - \frac{\psi}{1+\psi}\alpha\sum_j \eta_j P_{nj,t+1}Y_{nj,t+1}}\right].$$

Guess that each sector's investment is a fixed fraction of total GDP

$$P_{n,t}K_{nj,t+1} = \chi_j \sum_j \eta_j P_{nj,t}Y_{nj,t},$$

where $\sum_j \chi_j = \chi$. The Euler equation can be simplified as

$$\frac{\chi_j}{1-\chi-\alpha\frac{\psi}{1+\psi}} = \beta\frac{(1-\alpha)\eta_j}{1-\chi-\alpha\frac{\psi}{1+\psi}},$$

which leads to

$$\chi_j = \beta(1-\alpha)\eta_j, \quad \text{and} \quad \chi = \beta(1-\alpha)\sum_j \eta_j.$$

As a result, the changes in capital $K_{nj,t}$ is proportional to the changes in GDP $G_{n,t}$

$$\ln K_{nj,t+1} = \ln G_{n,t}.$$

The dynamics of GDP can therefore be represented as

$$\begin{aligned}
G_{n,t} &= \sum_j \omega_{nj}\left(\ln Z_{nj,t} + \alpha_j\eta_j \ln H_{nj,t} + (1-\alpha_j)\eta_j \ln K_{nj,t}\right) \\
&= \sum_j \omega_{nj}\left(\ln Z_{nj,t} + \alpha_j\eta_j \ln H_{nj,t} + (1-\alpha_j)\eta_j \ln G_{n,t-1}\right) \\
&= \sum_j \omega_{nj}\left(\ln Z_{nj,t} + (1-\alpha_j)\eta_j \ln G_{n,t-1} + \alpha_j\eta_j \sum_{m,i}\mathcal{H}_{nj,mi}\left(\ln Z_{mi,t} + \eta_i(1-\alpha_i)\ln K_{mi,t}\right)\right) \\
&= \sum_j \omega_{nj}\left(\ln Z_{nj,t} + (1-\alpha_j)\eta_j \ln G_{n,t-1} + \alpha_j\eta_j \sum_{m,i}\mathcal{H}_{nj,mi}\left(\ln Z_{mi,t} + \eta_i(1-\alpha_i)\ln G_{m,t-1}\right)\right).
\end{aligned}$$

Proof of Proposition 5.1. First consider the real wage in the baseline economy without wage rigidity. The labor supply condition is

$$\ln \mathbf{H}_t = \psi \ln \boldsymbol{w}_t^*.$$

This implies that

$$\ln \boldsymbol{w}_t^* = \frac{1}{\psi}\mathcal{H}(\ln \mathbf{Z}_t + (\mathbf{I}-\boldsymbol{\eta})\boldsymbol{\alpha}\ln \mathbf{K}_t) = \frac{1}{1+\psi}\left(\mathbf{I} + \left(\mathbf{I} - \boldsymbol{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right)\boldsymbol{\Lambda}(\psi),$$

where

$$\boldsymbol{\Lambda}(x) = \left(\mathbf{I} - \frac{x}{1+x}\boldsymbol{\eta}\boldsymbol{\alpha}\left(\mathbf{I} + \left(\mathbf{I} - \boldsymbol{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right) - (\mathbf{I}-\boldsymbol{\eta})\left(\mathbf{I} + (\mathbf{I} - \boldsymbol{\Pi}^x)\boldsymbol{\mathcal{P}}\right)\right)^{-1}.$$

Particularly,

$$\mathbf{\Lambda}(\infty) = \left(\mathbf{I} - \boldsymbol{\eta}\boldsymbol{\alpha}\left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right) - (\mathbf{I} - \boldsymbol{\eta})\left(\mathbf{I} + (\mathbf{I} - \mathbf{\Pi}^x)\boldsymbol{\mathcal{P}}\right)\right)^{-1}.$$

Now consider wage rigidity. The real wage obeys

$$\ln \boldsymbol{w}_t = (1-\lambda)\ln \boldsymbol{w}_t^* + \lambda \ln \boldsymbol{w}_{t-1}. \tag{B.15}$$

The labor market is demand determined, which leads to

$$\ln \boldsymbol{w}_t + \ln \mathbf{P}_t^f - \ln \mathbf{P}_t = \ln \mathbf{Y}_t - \ln \mathbf{H}_t. \tag{B.16}$$

Meanwhile, combining the production function and the optimal demand for intermediate goods gives

$$\ln \mathbf{Y}_t = \ln \mathbf{Z}_t + \boldsymbol{\eta}\boldsymbol{\alpha}\ln \mathbf{H}_t + \boldsymbol{\eta}(\mathbf{I}-\boldsymbol{\alpha})\ln \mathbf{K}_t + (\mathbf{I}-\boldsymbol{\eta})\left(\ln \mathbf{Y}_t + (\mathbf{I} - \mathbf{\Pi}^x)\ln \mathbf{P}_t\right). \tag{B.17}$$

When substituting condition (B.15) and (B.16) into condition (B.17), we have

$$\ln \mathbf{Y}_t = \mathbf{A}(\ln \mathbf{Z}_t + \boldsymbol{\eta}(\mathbf{I}-\boldsymbol{\alpha})\ln \mathbf{K}_t) - \lambda\mathbf{\Lambda}(\infty)\boldsymbol{\alpha}\boldsymbol{\eta}\ln \boldsymbol{w}_{t-1},$$

where $\mathbf{A}$ denotes the impact response

$$\mathbf{A} \equiv \mathbf{\Lambda}(\infty)\left(\mathbf{I} - \frac{1-\lambda}{1+\psi}\boldsymbol{\alpha}\boldsymbol{\eta}\left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right)\mathbf{\Lambda}(\psi)\right).$$

By the definition of the matrix function $\mathbf{\Lambda}(x)$, the impact response satisfies

$$\begin{aligned}
\mathbf{\Lambda}(\infty)^{-1}\mathbf{A}\mathbf{\Lambda}(\psi)^{-1} &= \mathbf{\Lambda}(\psi)^{-1} - \frac{1-\lambda}{1+\psi}\boldsymbol{\alpha}\boldsymbol{\eta}\left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right) \\
&= \mathbf{I} - \frac{\psi+1-\lambda}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right) - (\mathbf{I}-\boldsymbol{\eta})\left(\mathbf{I} + (\mathbf{I} - \mathbf{\Pi}^x)\boldsymbol{\mathcal{P}}\right) \\
&= \mathbf{\Lambda}\left(\frac{\psi+1-\lambda}{\lambda}\right)^{-1}.
\end{aligned}$$

Therefore, we have the desired result

$$\mathbf{A} = \mathbf{\Lambda}(\infty)\mathbf{\Lambda}\left(\frac{\psi+1-\lambda}{\lambda}\right)^{-1}\mathbf{\Lambda}(\psi).$$

Special case with complete markets. With complete markets, the relative marginal utility of consumption equals the real exchange rate

$$\frac{C_{n,t}^{-\sigma}}{C_{m,t}^{-\sigma}} = \frac{P_{n,t}}{P_{m,t}},$$

which implies

$$\ln P_{n,t} + \sigma \ln C_{n,t} = \ln P_{m,t} + \sigma \ln C_{m,t}.$$

Denote χ_t as

$$\chi_t \equiv \ln P_{n,t} + \sigma \ln C_{n,t}.$$

When normalizing the world nominal GDP to be 1, it follows that

$$\sum_m P_{m,t} C_{m,t} = 1,$$

which implies that

$$\sum_m P_m C_m (\ln P_{m,t} + \ln C_{m,t}) = 0.$$

When $\sigma = 1$, this condition reduces to

$$\chi_t = 0.$$

Also note that under the elasticities of substitution equal to 1 ($\rho = \varepsilon = 1$), the expenditure shares for both final goods and intermediate goods remain constant, which implies that for any country n sector j

$$\ln P_{nj,t} + \ln Y_{nj,t} = 0.$$

In labor markets, the labor supply satisfies the intratemporal Euler condition

$$C_{n,t}^{\sigma} H_{nj,t}^{\frac{1}{\psi}} = \frac{W_{nj,t}}{P_{n,t}},$$

and the linearized version is

$$\ln P_{n,t} + \sigma \ln C_{n,t} + \frac{1}{\psi} \ln H_{nj,t} = \ln W_{nj,t}.$$

When $\sigma = 1$, it follows that $\ln P_{n,t} + \ln C_{n,t} = 0$ and

$$\frac{1}{\psi} \ln H_{nj,t} = \ln W_{nj,t}.$$

The labor demand condition requires

$$\ln W_{nj,t} + H_{nj,t} = \ln P_{nj,t} + \ln Y_{nj,t}.$$

Since $\ln P_{nj,t} + \ln Y_{nj,t} = 0$ when $\rho = \varepsilon = 1$, it follows that

$$\ln H_{nj,t} = \ln W_{nj,t} = 0.$$

That is, hours remain constant in response to shocks, and the international comovements are only driven by correlated shocks.

B.2 Dynamic Model Solution Details

In this subsection, we provide more detail on the numerical algorithm in computing the dynamic model. An important feature of our problem is that the stochastic processes of the shocks are not known ex ante and need to be estimated based on the realized shocks, while the realized shocks are the result of the model inversion which requires the shock processes in the first place. That is, the shock processes are the solution to a fixed-point problem.

To make sure that the perceived laws of motion of both the shocks and endogenous equilibrium outcomes are consistent with the actual laws of motion, we apply the following iterative algorithm:

1. Solve for the matrix $\mathbf{M}$ using condition (B.13), which does not require the shock processes.
   (a) Make an initial guess $\mathbf{M}^{(0)}$.
   (b) Update the guess according to
   $$\mathbf{M}^{(1)} = -\mathbf{D}_1^{-1}\left(\mathbf{D}_0 + \mathbf{D}_2\left(\mathbf{M}^{(0)}\right)^2\right)$$
   (c) Replace the initial guess by $\mathbf{M}^{(1)}$ and iterate until convergence.
2. Solve for the matrix $\mathbf{\Gamma}$ and estimate the shock process $\boldsymbol{\varrho}$ jointly.
   (a) Make an initial guess $\boldsymbol{\varrho}^{(0)}$ that governs the autoregressive model (B.12).
   (b) Solve for the matrix $\mathbf{\Gamma}$ that satisfies condition (B.14):
      i. Make an initial guess $\mathbf{\Gamma}^{(0)}$
      ii. Update the guess according to
      $$\mathbf{\Gamma}^{(1)} = -(\mathbf{D}_1 + \mathbf{D}_2\mathbf{M})^{-1}\left(\mathbf{D}_2\mathbf{\Gamma}^{(0)}\boldsymbol{\varrho}^{(0)} + \mathbf{F}_1 + \mathbf{F}_2\boldsymbol{\varrho}^{(0)}\right)$$
      iii. Replace the initial guess by $\mathbf{\Gamma}^{(1)}$ and iterate until $\mathbf{\Gamma}^{(0)}$ and $\mathbf{\Gamma}^{(1)}$ converge.
   (c) Obtain the shocks that match the observed value added growth at each country sector. Recall that by Proposition 3.2, the vector of value added is given by
   $$\ln \mathbf{V}_t = \ln \mathbf{Z}_t + \boldsymbol{\alpha}\boldsymbol{\eta} \ln \mathbf{H}_t + (\mathbf{I} - \boldsymbol{\alpha})\boldsymbol{\eta} \ln \mathbf{K}_t.$$
   Assume that the shocks before the first observation of the data are zero. It follows that
   $$\ln \mathbf{V}_0 = \ln \mathbf{Z}_0 + \boldsymbol{\alpha}\eta\mathcal{H} \ln \mathbf{Z}_0,$$
   and for $t > 0$
   $$\ln \mathbf{V}_t = \ln \mathbf{Z}_t + \boldsymbol{\alpha}\boldsymbol{\eta}\mathcal{H}\left(\ln \mathbf{Z}_t + \sum_{k=0}^{t-1} \mathbf{M}^{t-k-1}\mathbf{\Gamma} \ln \mathbf{Z}_k\right) + (\mathbf{I} - \boldsymbol{\alpha})\boldsymbol{\eta}\left(\ln \mathbf{Z}_t + \sum_{k=0}^{t-1} \mathbf{M}^{t-k-1}\mathbf{\Gamma} \ln \mathbf{Z}_k\right),$$
   where the sequence of capital is given by
   $$\ln \mathbf{K}_t = \sum_{k=0}^{t-1} \mathbf{M}^{t-k-1}\mathbf{\Gamma} \ln \mathbf{Z}_k.$$
   By matching the data on $\ln \mathbf{V}_t$, one can recover the sequence of shocks $\{\ln \mathbf{Z}_t\}$.
   (d) Estimate the new shock process according to
   $$\ln Z_{nj,t} = \rho_{nj} \ln Z_{nj,t-1} + \zeta_n \mathbf{1}\left(m = n, k \neq j\right) \ln Z_{mk,t-1} + \theta_{nj,t},$$
   where we allow the dependence on its own past value and the past values within the same country. The estimated coefficients enter the new shock process matrix $\boldsymbol{\varrho}^{(1)}$.

(e) Replace the initial guess of the shock process by $\varrho^{(1)}$ and iterate until convergence.

This algorithm makes sure that the perceived laws of motion and the actual laws of motion are the same.

B.3 Exact Solution to the Static Network Model

This section sets up the exact solution to the static network model, in changes, following the methodology of Dekle, Eaton, and Kortum (2008). In this section, denote by a "hat" the gross proportional change in any variable between the steady state x and a counterfactual x_t: $\widehat{x} \equiv x_t/x$. To streamline notation, define $\mathcal{Y}_{nj,t} \equiv P_{nj,t}Y_{nj,t}$ to be the gross revenue in sector j, country n. Following a set of supply shocks $\widehat{Z}_{nj,t}$, the price in sector j, country n experiences the change:

$$\widehat{P}_{nj,t} = \widehat{Z}_{nj,t}^{-1}\widehat{\mathcal{Y}}_{nj,t}^{(1-\alpha_j)\eta_j-\frac{1}{\psi+1}\alpha_j\eta_j}\widehat{P}_{n,t}^{\alpha_j\eta_j\frac{\psi+1}{\psi}}\left(\sum_{m,i}\pi_{mi,nj}\widehat{P}_{mi,t}^{1-\varepsilon}\right)^{\frac{1-\eta_j}{1-\varepsilon}}. \tag{B.18}$$

This, together with the dependence of $\widehat{P}_{n,t}$ on the constituent $\widehat{P}_{ni,t}$:

$$\widehat{P}_{n,t} = \left[\sum_i\sum_m \widehat{P}_{mi,t}^{1-\rho}\pi_{mni}^{f}\right]^{\frac{1}{1-\rho}} \tag{B.19}$$

defines a system of $J\times N$ equations in prices, conditional on known steady-state data quantities (such as π_{mni}^{f}), and a vector of $\widehat{\mathcal{Y}}_{nj,t}$'s. The price changes in turn determine the counterfactual shares (denoted by a t-subscript):

$$\pi_{nmj,t}^{f} = \frac{\widehat{P}_{nj,t}^{1-\rho}\pi_{nmj}^{f}}{\sum_k \widehat{P}_{kj,t}^{1-\rho}\pi_{kmj}^{f}}, \tag{B.20}$$

$$\pi_{nj,mi,t}^{x} = \frac{\widehat{P}_{nj,t}^{1-\varepsilon}\pi_{nj,mi}^{x}}{\sum_{k,\ell}\widehat{P}_{k\ell,t}^{1-\varepsilon}\pi_{k\ell,mi}^{x}}. \tag{B.21}$$

These trade shares have to be consistent with market clearing at the counterfactual t, expressed using proportional changes as:

$$\widehat{\mathcal{Y}}_{nj,t}\mathcal{Y}_{nj} = \sum_m\left[\pi_{nmj,t}^{f}\omega_{jm}\left(\sum_i\eta_i\widehat{\mathcal{Y}}_{mi,t}\mathcal{Y}_{mi}\right)+\sum_i\pi_{nj,mi,t}^{x}\left(1-\eta_i\right)\widehat{\mathcal{Y}}_{mi,t}\mathcal{Y}_{mi}\right]. \tag{B.22}$$

The sets of equations (B.18)-(B.22) represent a system of $2\times N\times J+N^2\times J+N^2\times J^2$ unknowns, $\widehat{P}_{nj,t}$ $\forall n,j$, $\widehat{\mathcal{Y}}_{nj,t}$ $\forall n,j$, $\pi_{nmj,t}^{f}$ $\forall n,m,j$, and $\pi_{nj,mi,t}^{x}$ $\forall n,j,m,i$ that is solved under given parameter values and under a set of shocks $\widehat{Z}_{nj,t}$.

B.3.1 Algorithm for Exact Solution to the Static Model

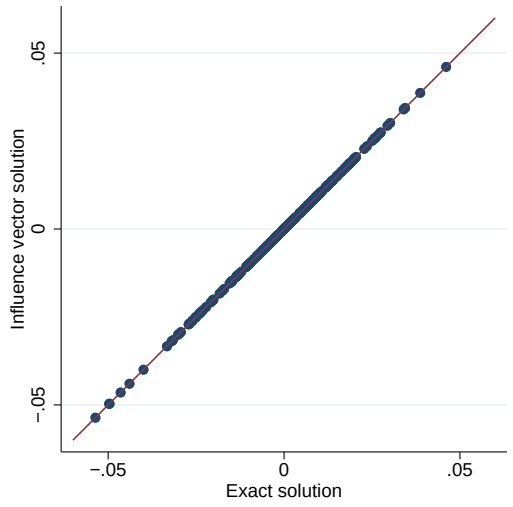
To solve the model, we use an initial guess for $\widehat{\mathcal{Y}}_{nj,t}$ together with data on π_{mnj}^{f} and $\pi_{nj,mi}^{x}$. Given these variables, the algorithm is as follows:

1. Solve for $\widehat{P}_{nj,t}$ given the guess of $\widehat{\mathcal{Y}}_{nj}$ and the data on π^{f}_{mnj} and $\pi^{x}_{nj,mi}$. This step uses equations (B.18) and (B.19) .
2. Update $\pi^{f}_{mnj,t}$ and $\pi^{x}_{nj,mi,t}$ given the solution to step 1 using equations (B.20) and (B.21).
3. Solve for the new guess $\widehat{\mathcal{Y}}'_{nj,t}$ using equation (B.22) given the prices $\widehat{P}_{nj,t}$ obtained in step 1 and the updated shares $\pi^{f}_{mnj,t}$ and $\pi^{x}_{nj,mi,t}$ from step 2.
4. Check if $\max|(\widehat{\mathcal{Y}}'_{nj,t} - \widehat{\mathcal{Y}}_{nj,t})| < \delta$, where δ is a tolerance parameter that is arbitrarily small. If not, update the guess of $\widehat{\mathcal{Y}}_{nj,t}$ and repeat steps 1-4 until convergence.

B.3.2 Comparison of the Exact and First-Order Solutions

Figure A3 presents a scatterplot of GDP growth rates obtained under the first-order analytical solution to the global influence matrix in Section 3.2 against the exact solution computed as in this appendix. The line through the data is the 45-degree line. The GDP growth rates are computed under the observed shocks, and pooled across countries and years. It is clear that the first-order approximation is quite good in essentially every country-year instances. The correlation between the two sets of growth rates is 0.998. Table A3 summarizes the GDP correlations obtained using GDP growth rates in the linear and exact solutions. The correlations are very close to each other.

Figure A3: Comparison of GDP Growth Rates between First-Order and Exact Solutions



Notes: This figure displays a scatterplot of the GDP growth rates obtained using the first-order approximation against the GDP growth rates in the exact solution to the model, pooling countries and years. The line through the data is the 45-degree line.

B.3.3 When is the First-Order Solution Reasonable?

We next turn to the question of when using the first-order solution provides a reasonable approximation to the exact solution. Baqaee and Farhi (2019) argue that higher-order effects can be quantitatively relevant in non-linear network economies, particularly when the shock size is large. Figure A3 illustrated that for our actual recovered shocks, the exact and first-order solution are nearly identical. To

Table A3: First-Order and Exact Solutions: Correlations of $d \ln G_{n,t}$, G7 Countries

	Mean	Median	25th pctile	75th pctile
		N. obs. = 21		
Static model (approx.)	0.350	0.356	0.124	0.558
Exact solution	0.350	0.356	0.230	0.558

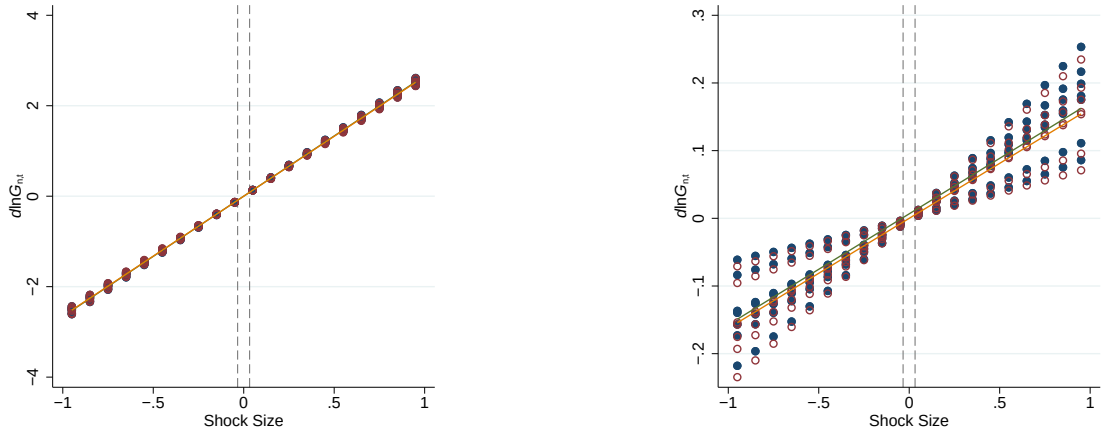
Notes: This table presents the summary statistics of the correlations of the model $d \ln G_{n,t}$ in the sample of G7 countries computed using the linear approximation and the exact solution. Variable definitions and sources are described in detail in the text.

explore the size of shocks for which the linear solution would yield a worse approximation, Figure A4 plots the log changes in GDP under the first order (red hollow circles) and exact (solid blue dots) for all countries following 4 shocks. The lines plot the averages across countries for each size shock. In each case, the size of the shocks, in logs, is on the x-axis. The first is a "Global" shock, where all country-sectors receive a shock of the same size. This is an extreme example of a perfectly correlated shock. The second is a scenario in which the "Rest-of-the-World" receives a shock, but the domestic country in question is not shocked. The third is a purely domestic shock, while all trade partners receive no shock. Finally, we consider the responses of all countries to a US shock. In all exercises, the size of the shock is symmetric across sectors within a country that is shocked, and across countries in the instance where several countries are shocked. In the Rest-of-the-World and Domestic scenarios, we solve the exact model country by country. For reference, we also include lines illustrating the 5th and 95th percentile of the sectoral shocks recovered in the data.

It is immediate that non-linearities increase in importance for larger shock sizes. This is true for all four types of shocks. However, there are a number of interesting nuances. First, in the case of the Global shock, even for extremely large shocks (a 50-95% increase or decrease in $d \ln Z$), the difference in the exact and linearized solution is fairly small. Intuitively, in the case of a common shock, there is little relative change in sectoral sizes across countries, which decreases the size of the higher-order terms missed by the linear approximation. In the context of even large correlated shocks such as the Covid-19 pandemic, this suggests that our influence matrix analytical solution is useful. Second, the difference between the exact and linearized model can be large but only in when the shock sizes are very large (90-95%), and induce large changes in relative sector sizes, as is true in panels (b) and (d) when either the rest-of-the world is shocked or there is a very large US shock. In the case of a US shock, only its closest trading partner Canada sees a noticeable discrepancy between the exact and first-order solution, and that is still only about 5 percentage points for a US shock of 95% in all sectors.

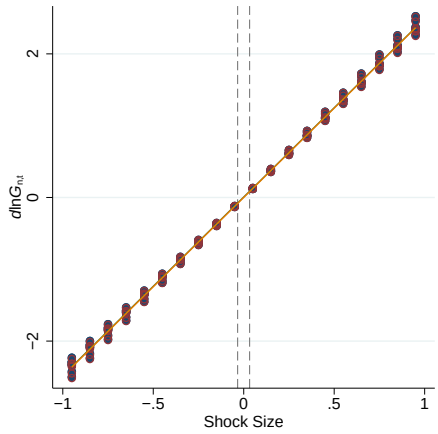
This discussion suggests that while non-linearities can be quantitatively important in some extreme cases, in the empirically relevant range of shocks observed in the data using the linearized model is reasonable. Additionally, the shocks recovered in Section 4 were found to be very correlated. Our analysis illustrates that this is precisely the instance where, even if the shocks are larger, the linearized model is a good approximation of the exact solution.

Figure A4: Comparison of GDP Growth Rates between First-Order and Exact Solutions for Varied Shock Sizes

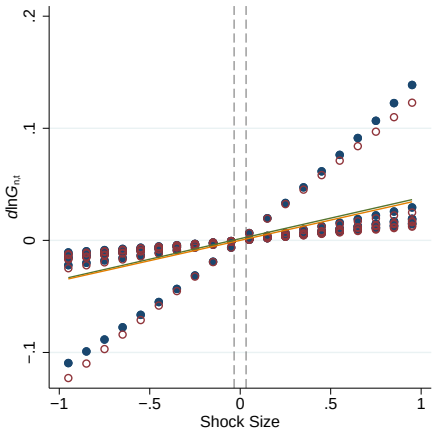


(a) Global Shock

(b) Rest-of-the-World Shock



(c) Domestic Shock



(d) US Shock

Notes: This figure displays the GDP growth rates obtained using the exact solution (solid blue dots) and the first-order approximation to the model (hollow red circles) for varied shock sizes under different scenarios. Panel (a) shows the results for all countries when every country and sector has the same sized shock. Panel (b) shows the results when every country and sector except the country in question has a same sized shock ("rest-of-the world shock"). Panel (c) shows the results when only the country in question has the same sized shock in all sectors ("domestic shock") and Panel (d) shows the results when only the US has a shock in every sector ("US Shock"). The solid lines show the cross-country averages at each size shock. The vertical dashed lines show the 5th and 95th percentiles of the actual shocks recovered from the G7 data over the period 1978-2007.

C. Estimation

C.1 Estimation of ρ and ε

We use model-implied relationships to estimate ρ and ε. In this section, denote by a "hat" the gross proportional change in any variable between time t and the previous year: $\widehat{x}_t \equiv x_t/x_{t-1}$. Further assume that iceberg trade costs, final consumer taste shocks, and input share shocks have a stochastic element, and denote their gross proportional changes by $\widehat{\tau}_{mnj,t}$, $\widehat{\vartheta}_{mnj,t}$, and $\widehat{\mu}_{mj,ni,t}$, respectively. This helps interpret the error term in the estimating equations. Log-differencing the CES expenditure shares (3.5) and (3.10) first with respect to $t-1$ and then with respect to a reference country m' yields the following relationships between shares and prices:

$$\ln\left(\frac{\widehat{\pi}^f_{mnj,t}}{\widehat{\pi}^f_{m'nj,t}}\right) = \left(1-\rho\right)\ln\left(\frac{\widehat{P}_{mj,t}}{\widehat{P}_{m'j,t}}\right) + \ln\left(\frac{\widehat{\vartheta}_{mnj,t}\widehat{\tau}^{1-\rho}_{mnj,t}}{\widehat{\vartheta}_{m'nj,t}\widehat{\tau}^{1-\rho}_{m'nj,t}}\right) \tag{C.1}$$

and

$$\ln\left(\frac{\widehat{\pi}^x_{mj,ni,t}}{\widehat{\pi}^x_{m'j,ni,t}}\right) = (1-\varepsilon)\ln\left(\frac{\widehat{P}_{mj,t}}{\widehat{P}_{m'j,t}}\right) + \ln\left(\frac{\widehat{\mu}_{mj,ni,t}\widehat{\tau}^{1-\varepsilon}_{mnj,t}}{\widehat{\mu}_{m'j,ni,t}\widehat{\tau}^{1-\varepsilon}_{m'nj,t}}\right). \tag{C.2}$$

We express the expenditure share change $\widehat{\pi}^f_{mnj,t}$ relative to the expenditure share change in a reference country m'. In the baseline estimation, this reference country is chosen separately for each importing country-sector (n, j) as the country with the largest average expenditure share in that country-sector. (Thus, strictly speaking, the identity of the reference country m' is distinct for each importing country-sector, but we suppress the dependence of m' on (n, j) to streamline notation.)

The estimation amounts to regressing double-differenced expenditure share changes on relative price changes. A threat to identification would be that relative source country price changes are affected by destination country demand shocks (e.g. $\widehat{\vartheta}_{mnj,t}$), and thus correlated with the residual. We address endogeneity by means of three strategies. First, to absorb as much of the confounding variation as possible, we include source-destination-reference country-time ($n \times m \times m' \times t$) fixed effects. These absorb many possible confounders including any common components occurring at the country 3-tuple-time level, such as exchange rate changes and other taste and transport cost changes, and thus the coefficient is estimated from the variation across sectors in relative price indices and relative share movements within that cell.

Second, our estimates are based on the subsample in which destination countries are all non-G7, and the source and reference countries are all G7 countries. In this sample it is unlikely that taste shocks in the (smaller) destination countries will affect relative price changes in the larger G7 source countries. This sample restriction by construction also implies that all the own expenditure shares $\widehat{\pi}^f_{nnj,t}$ are dropped from the estimation sample. This is desirable since the domestic shares are computed as residuals in WIOD, whereas import shares from other countries are taken directly from the international trade data. To reduce the impact of small shares on the estimates, we report results weighting by the size of the beginning-of-period expenditure shares ($\pi^f_{mnj,1995}$ and $\pi^x_{mj,ni,1995}$), and consider alternative weights as robustness checks.

Third, in addition to the steps described above to mitigate endogeneity issues, we use TFP shocks as instruments for changes in relative prices. Thus, we use for estimation only the variation in the relative price change $\widehat{P}_{mj,t}/\widehat{P}_{m'j,t}$ that is attributable to foreign TFP shocks. The exclusion restriction is that the technology shocks are uncorrelated with taste and trade cost shocks in the relevant sample and net of the fixed effects, and thus only affect the share ratios through changing the prices.

The expenditure shares on the left-hand side are sourced from WIOD. Because the WIOD expenditure shares are only available starting in 1995, the years present in the estimation sample are 1995-2007. The price changes on the right-hand side are the output price indices (GO_P) from KLEMS. It must be noted that the WIOD applies the proportionality assumption to construct intermediate input expenditure shares. That is, there exist actual data the total amount of sector j intermediate inputs country n imports from country m. However, from then on a proportionality assumption is applied to attribute these imported inputs to using sectors i. Thus, there is no variation in $\widehat{\pi}^{x}_{mj,ni,t}$ across i within the same $m \times j \times n$ cell. To avoid artificially multiplying the number of observations in the sample by a factor of J, we only use one using sector i per $m \times j \times n$ cell as the estimation sample. We cluster the standard errors at the destination-source-reference country level.

The TFP instruments are the Solow residuals constructed in a standard way from the KLEMS data. Thus, importantly, the TFP shocks used as instruments in this estimation are *not* the composite supply shocks recovered in Section 4.3.

Table A4 presents the results of estimating equations (C.1) and (C.2). Column 1 reports the OLS estimates of ρ (top panel) and ε (bottom panel). The OLS estimate of ρ is 0.94, close to a Cobb-Douglas final demand elasticity. Column 2 instruments the price changes with TFP changes. The elasticity estimate rises to 1.43. Column 3 weights by the initial expenditure shares. The coefficient estimate does not change. Columns 4-5 implement alternative weights, – average and $t-1$ expenditure shares, respectively. Column 6 uses utilization-adjusted TFP from Huo, Levchenko, and Pandalai-Nayar (2023) as instruments instead. Column 7 uses all available countries (rather than non-G7 destinations and G7 sources only). Column 8 keeps the reference country the same in the top and bottom panels.[2] Across all robustness checks, the estimates of ρ are fairly stable, ranging between 1.4 and 1.7, and significantly larger than 1 in most cases. This difference between OLS and IV suggests measurement error in (C.1). The KP-F statistics are larger than conventional thresholds in almost all cases, although they are only 9.23 when the utilization-adjusted TFP instrument is used in Column 7.

The OLS and IV estimates of display somewhat greater consensus for ε. The OLS point estimate of ε is 0.94. The baseline IV estimates are slightly lower at 0.89. Across the same range of robustness checks as above, the range of estimates is 0.86-1.2. Such evidence for the low substitutability of intermediate inputs is consistent with the recent estimates by Atalay (2017) and Boehm, Flaaen, and Pandalai-Nayar (2019), who find even stronger complementarity, albeit with even shorter frequencies than our annual data.

We use the estimates of $\rho = 1.43$ and $\varepsilon = 0.89$ in column 3 as our baseline calibration. However, it is clear that economically and statistically the IV estimates are stable across a number of robustness checks.

C.2 Estimation of ψ

We use the responses of labor hours to shocks to estimate ψ. To do this in a theory-consistent way, we have to use the structure of the model. The labor supply in vector notation is:

$$\ln \mathbf{H}_t = \psi(\ln \mathbf{W}_t - \mathbf{\Pi}^f \ln \mathbf{P}_t),$$

Turning to the production side, the labor demand (3.8) stacked into an $NJ \times 1$ vector is:

$$\ln \mathbf{W}_t - \ln \mathbf{P}_t = \ln \mathbf{Y}_t - \ln \mathbf{H}_t.$$

[2] For robustness, we have also used the US as the reference country for all other countries.

Table A4: Estimates of ρ and ε

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			Alternative Weights			Varied Instruments		Varied Samples
	OLS	IV	IV	IV	IV	IV	IV	IV
ρ	0.94	1.43	1.43	1.41	1.51	1.68	1.52	1.49
SE	(0.03)	(0.16)	(0.09)	(0.09)	(0.15)	(0.19)	(0.14)	(0.12)
Obs	152,742	115,195	114,931	115,195	115,195	114,931	414,129	114,299
First stage K-P F		245.71	90.79	94.51	82.87	9.23	161.49	69.42
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ε	0.94	0.86	0.89	0.96	0.97	1.10	1.15	0.89
SE	(0.02)	(0.20)	(0.17)	(0.08)	(0.34)	(0.29)	(0.12)	(0.17)
Obs	146,093	114,701	114,467	114,701	114,701	114,372	415,377	114,467
First stage KP-F		285.42	307.8	345.29	363.25	31.83	129.45	307.80
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weights			Baseline	Average	Lagged	Baseline	Baseline	Baseline
Instrument		Baseline	Baseline	Baseline	Baseline	Utilization-adjusted TFP	Baseline	Baseline
Sample	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	All countries	Constant Reference

Notes: Standard errors clustered at the destination-source-reference country level in parentheses. This table presents results from the OLS and IV estimation of (C.1) and (C.2). The fixed effects used in each regression are $n \times m \times m' \times t$. The instruments are the relative Solow residuals, with the Kleibergen-Papp first stage F-statistic reported except in Column 6 where they are relative utilization-adjusted TFP shocks estimated in Huo, Levchenko, and Pandalai-Nayar (2023). The "baseline" weights in columns 3, 6, 7 and 8 are the 1995 share ratios. Column 4 uses an average share ratio as weights and column 5 uses lagged share ratios $\pi^f_{mnj,t-1}$ and $\pi^x_{mj,ni,t-1}$. All columns use the baseline sample of G7 source countries/non G7 destinations except column 7 which uses all source and destination countries. Column 8 uses a constant reference country for estimating ρ and ε.

This means that

$$\begin{aligned}
\ln \mathbf{H}_t &= \frac{\psi}{1+\psi}(\ln \mathbf{Y}_t + (\mathbf{I} - \mathbf{\Pi}^f \ln \mathbf{P}_t) \\
&= \frac{\psi}{1+\psi}(\ln \mathbf{Y}_t + (\mathbf{I} - \mathbf{\Pi}^f \boldsymbol{\mathcal{P}} \ln \mathbf{Y}_t) \\
&= \frac{\psi}{1+\psi}\left(\mathbf{I} + (\mathbf{I} - \mathbf{\Pi}^f \boldsymbol{\mathcal{P}}\right) \mathbf{\Lambda} \ln \mathbf{Z}_t \\
&= \boldsymbol{\mathcal{H}}(\psi, \rho, \varepsilon) \ln \mathbf{Z}_t.
\end{aligned}$$

This equation, which relates changes in equilibrium nominal wages and equilibrium prices $\ln \mathbf{W}_t - \mathbf{\Pi}^f \ln \mathbf{P}_t$ to changes in equilibrium hours $\ln \mathbf{H}_t$, can be used to estimate ψ.

The derivation of this equation makes clear that the vector of TFP shocks $\ln \mathbf{Z}_t$ act as both labor demand shifters through their effect on $\ln \mathbf{Y}_t$, but also as labor supply and demand shifters through their effects on equilibrium final goods prices $\mathbf{\Pi}^f \ln \mathbf{P}_t$ and firm intermediate goods prices $\ln \mathbf{P}_t$. This is a threat to identification, as to estimate the labor supply elasticity ψ, we need to isolate shocks that shift the labor demand curve but hold the labor supply curve approximately constant. An additional threat to identification is shocks to labor supply. Introducing an explicit labor supply shock, as in the

multi-shock model in Section 5.2, labor supply can be written as:

$$\ln H_{nj,t} = \psi \left(\ln W_{nj,t} - \ln P_{n,t} \right) + \psi \left(1 - \xi^H_{nj,t} \right). \tag{C.3}$$

To the extent that the labor supply shocks $\xi^H_{nj,t}$ are correlated with the $\ln \mathbf{Z}_t$ that are driving the shifts in labor demand through their equilibrium impact on $\ln W_{nj,t}$, the labor supply shocks present an additional threat to identification. As a result, we cannot simply estimate ψ by regressing hours on either observed or model-implied wages. In fact, if TFP shocks in some sectors increase using sector labor demand and also decrease the final goods price index for consumers, thereby decreasing labor supply, we would expect the estimate of ψ from a regression of hours growth on wage changes to be biased towards zero.

To address this issue, we select a plausibly exogenous set of $\ln \mathbf{Z}_t$ shocks, and use them to estimate the labor supply elasticity. Our strategy is loosely inspired by the Shea (1993a,b) instruments that have been used to estimate the elasticity of industry supply curves. These papers use the patterns of input-output relationships to select subsets of sectors that are important downstream destinations for a sector's sales – thereby acting as a demand shifter — but are not themselves important sources of inputs to those downstream sectors. In that case, the sector subset can be viewed as shifting industry output demand curves without simultaneously shifting industry cost curves, permitting estimation of an output supply elasticity. We follow a similar approach. In our context we need to isolate plausibly exogenous movements in industry *labor* demand.

The set of sectors we treat as exogenous is an intersection of two sets. The first is the set of sectors least important in final consumption. TFP shocks in these sectors will have minimal impact on the final goods price index, and therefore, minimal impact on the household's labor supply to any sector. Precisely, following Shea (1993a,b), for each country we retain the 10% of all sectors with the lowest consumption shares. This limits potential endogeneity from labor supply shifts. To obtain a set of instruments that are relevant, we next isolate the set of sectors is the top 30% most important suppliers for a using sector. Shocks to these sectors will affect the input price bundle, and shift labor demand for the using sector. Selecting the intersection of these two sets picks out sectors that are not important in final consumption, but are important as input suppliers.

Intuitively, these are sectors whose shocks are likely to be the pure labor demand shocks for the using sector: productivity improvements in a sector's intermediate input suppliers will increase labor demand in those sectors. At the same time, because these sectors are not important in final consumption, shocks to those sectors are not shifting labor supply to the using sector. There remains the possibility that the exogenous (admitted) shocks are correlated with the potentially endogenous (excluded) shocks, and other labor supply shocks. We use the sectoral Solow residuals as the shocks $\ln \mathbf{Z}_t$. In our earlier work (Huo, Levchenko, and Pandalai-Nayar, 2023), we found that the Solow residuals have at most a modest correlation across country-sectors. Thus, the correlation between the residuals and the admitted exogenous shocks is likely minimal. To clean out any remaining common component from these shocks, we take out the time fixed effects from the panel of shocks.[3]

Note that the matrix $\boldsymbol{\mathcal{H}}(\psi, \rho, \varepsilon)$ that relates shocks to hours responses is a function of ρ and ε. In addition, $\boldsymbol{\mathcal{H}}(\psi, \rho, \varepsilon)$ is a nonlinear function ψ, and thus we use the Non-Linear Least Squares estimator:

$$\hat{\psi} = argmin_{\psi} \left(\ln \mathbf{H}_t - \left(\boldsymbol{\Lambda}^H \left(\psi, \rho, \varepsilon \right) \cdot \mathbf{S} \right) \ln \mathbf{Z}_t \right)^2, \tag{C.4}$$

where $\mathbf{S}$ is the selection matrix, whose entries are either 0's or 1's, that picks out for each destination country-sector (n, j) the exogenous set of sectors, as described above.

[3] We have also assessed whether the admitted shocks, after fixed effects, are correlated with the labor shocks we back out in Section 5.2. We found no correlation.

The maintained identifying assumption is that *each* of the Solow residuals in the exogenous set of sectors for each sector (n, j) is orthogonal to the error term in sector (n, j). While in principle we could introduce a separate NLS estimating equation for each exogenous sector and using sector and estimate a range of ψ's using exclusively time variation, this is both very cumbersome and likely to be very noisy as the time series is relatively short. We gain statistical power by pooling all equations together and estimating a single ψ that minimizes (C.4).

This requires that the transformed *sum* of the Solow residuals in the exogenous set of sectors is orthogonal to the error term for each destination sector. Of course, the maintained identifying assumption that each excluded sector is orthogonal is a sufficient albeit not necessary condition for their sum to be orthogonal. We favor this approach as (C.4) is the most parsimonious condition that allows us to estimate ψ on the pooled dataset of countries, sectors, and years.

Our baseline estimate of ψ using this procedure is 0.723. Note that it is very close to the Frisch elasticity suggested by Chetty et al. (2011) as appropriate for macro models. This is reassuring, as our sectoral data and quantitative setting are not the ideal setting to estimate the labor supply elasticity due to a number of measurement challenges. In particular the composition of hours worked is likely to vary importantly over the cycle (e.g. Solon, Barsky, and Parker, 1994). Compounding the problem, the nonlinear relationship between the Frisch elasticity and the hours' response to shocks makes it challenging to estimate ψ. As we acknowledge the limitations of our setting for estimating the Frisch elasticity, we also report results when using the value of $\psi = 0.75$ suggested Chetty et al. (2011), treating it as an externally calibrated parameter.

The NLS estimator is also a function of the elasticities ρ and ε estimated above. To take into account how the uncertainty over ρ and ε translates into uncertainty over ψ, we draw 1000 times from the distributions of ρ and ε estimated above, and estimate ψ under each of these pairs of ρ and ε.[4] Taking the distribution of estimates of ψ across the draws of ρ and ε gives us the empirical marginal distribution of ψ. Figure A5 displays the histogram of estimates of ψ. As ρ and ε vary, the resulting distribution of ψ is centered around the baseline value, but with a thicker upper tail.

C.3 Estimation of Shock Processes

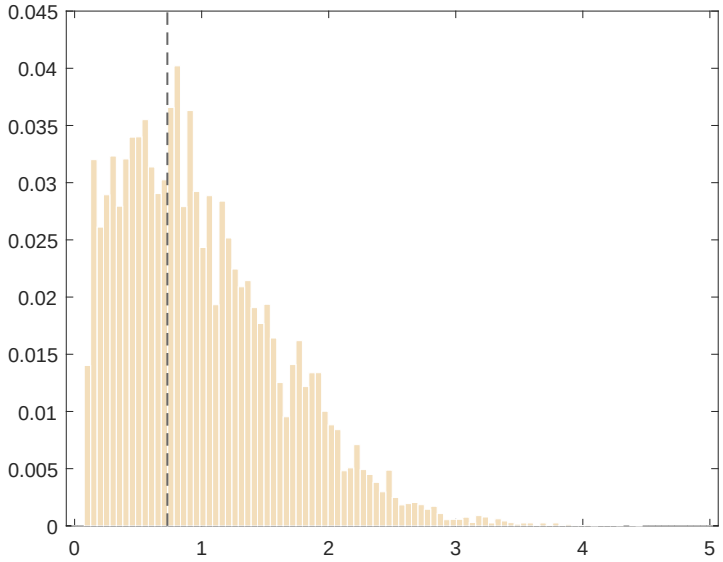
The estimation sample is the G7 countries, for which we have the longest time series of shocks. As discussed in Section 4, while estimating an unrestricted process for shocks is not possible due to the short panel of measured shocks and the large number of parameters to be estimated, we impose minimal restrictions that allow the shocks to be correlated (as the measured shocks are), and further, allow for spillovers between country-sectors.

Equations (4.2)-(5.4) state the estimating equations for the shock processes in the one- and four-shock models respectively. In particular, our specification allows for contemporaneous shock correlations between country-sectors, but restricts the structure of lagged spillovers. We permit a country-sector specific lagged autoregressive parameter, so country-sector shocks can be persistent. We restrict lagged spillovers to be common within a country (across sectors), and zero otherwise. We allow for a full variance-covariance matrix of the error terms, which amounts to assuming completely unrestricted contemporaneous spillovers. The sample variance-covariance matrix of the residuals serves as the estimate of the covariance matrix of the shock innovations.

The choice of restrictions strikes a balance between relative parsimony, which improves the precision of the parameters estimated, and sufficient flexibility to replicate the measured shock correla-

[4]Note, we assume that the distributions of ρ and ε are independent. We have experimented with estimating (C.1) and (C.2) by Seemingly Unrelated Regressions (SURs). The results suggested close to zero covariance between the estimates, implying our assumption of independence is reasonable. We do not use these estimates as our baseline, as existing econometric tools to estimate SURs with separate instruments do not permit clustering of standard errors, and thus in our setting produce artificially low standard errors.

Figure A5: The distribution of ψ



Notes: This figure displays the histogram of the values of ψ estimated by (C.4), drawing 1000 times from the distributions of ρ and ε implied by estimates in column 3 of Table A4. The vertical dashed line is the baseline point estimate of ψ.

tions in the data. We experimented with other processes using methods such as LASSO regressions to estimate the process for the intertemporal shocks without much change to the simulated shock correlations. In particular, we have modified the estimating equations to also include a sector-specific lagged spillover term, but these coefficients were all insignificant, and so we use the more parsimonious process in the baseline analysis. Table A5 summarizes the estimation results.

Table A5: Shock Processes: Autoregressive and Spillover Parameters

	Mean	Median	25th pctile	75th pctile
One-Shock Model				
			$\ln Z_{nj,t}$	
Own lag (ρ_{nj})	0.862	0.880	0.831	0.886
Spillover lag (δ_n)	-0.001	-0.002	-0.002	0.000
Four-Shock Model				
			$\ln \xi^Z_{nj,t}$	
Own lag (ρ_{nj})	0.877	0.875	0.862	0.894
Spillover lag (δ_n)	-0.002	-0.002	-0.002	-0.001
			$\ln \xi^X_{nj,t}$	
Own lag (ρ_{nj})	0.852	0.848	0.837	0.869
Spillover lag (δ_n)	0.002	0.002	0.001	0.002
			$\ln \xi^H_{nj,t}$	
Own lag (ρ_{nj})	0.901	0.904	0.888	0.917
Spillover lag (δ_n)	-0.001	-0.001	-0.002	0.000
			$\ln \xi^I_{nj,t}$	
Own lag (ρ_{nj})	0.930	0.933	0.929	0.935
Spillover lag (δ_n)	-0.005	-0.005	-0.005	-0.005

Notes: This table presents results from estimating the shock stochastic processes (4.2)-(5.4). The "One-Shock Model" panel presents the results for the composite shock estimated and used in Section 4. The "Four-Shock Model" panel presents the results for the 4 shocks estimated and used in Section 5.2. The measures are summary statistics of the coefficients in the sample of sectors and countries.

D. Sensitivity and Additional Exercises

D.1 Sensitivity

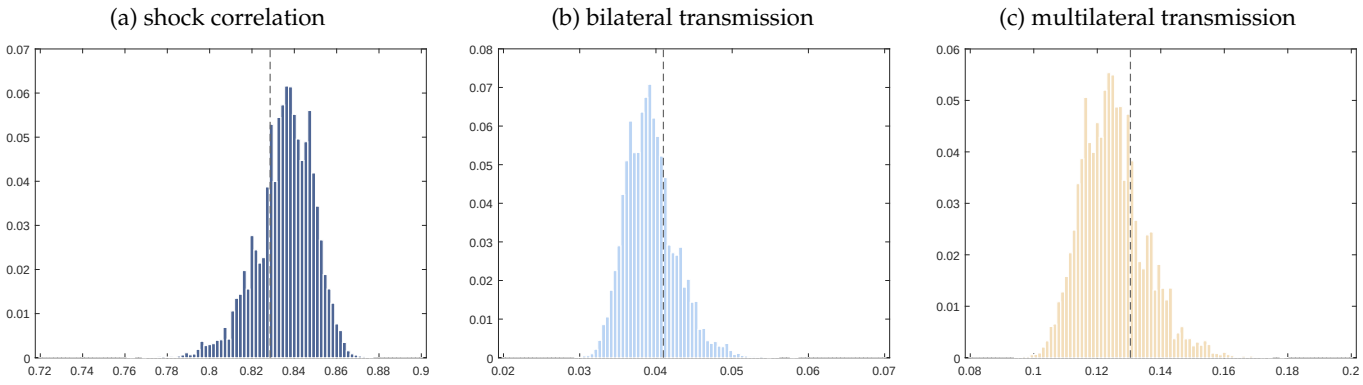
This subsection reports various sensitivity exercises for the network model results in Sections 3-4.

Table A6: GDP Growth and HP-Filtered GDP Correlation in G7 Countries

	Mean	Median	25th pctile	75th pctile	St.dev. (GDP)
GDP growth rate	0.358	0.333	0.122	0.552	1.667
HP-Filtered GDP	0.395	0.460	0.040	0.585	1.736

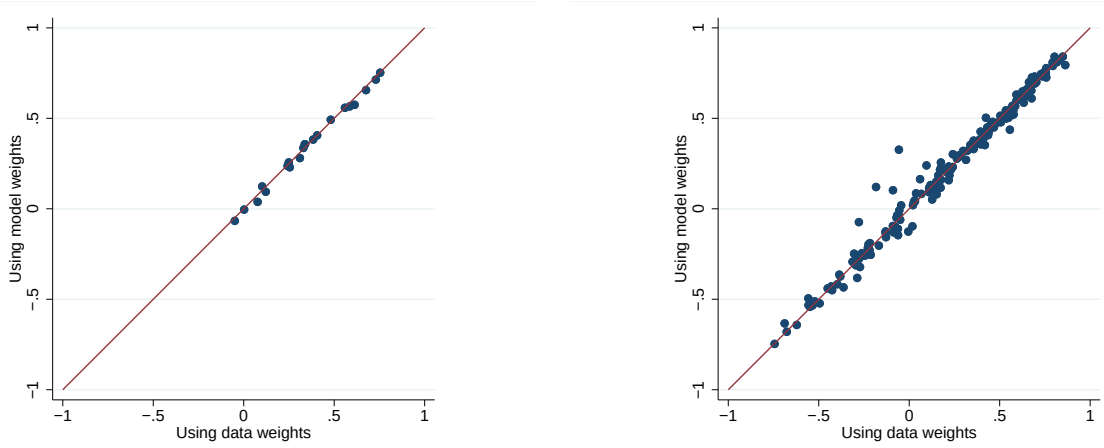
Notes: This table presents the summary statistics of the correlations of GDP growth rates and HP-filtered GDP in the sample of G7 countries. We use $\lambda = 100$ for the HP-filter parameter, as the data are annual.

Figure A6: Distribution of Direct Effects versus Transmission



Notes: This figure displays the distribution of relative contribution of shock correlation, bilateral transmission and multilateral transmission to international comovements in the G7 countries. The elasticities of substitution ρ and ε are drawn from normal distributions and the Frisch elasticity ψ is fixed at 0.72.

Figure A7: GDP Correlations Under Data and Model Domar Weights



G7 All Countries

Notes: This figure displays a scatter plot of the GDP growth correlation, when GDP growth is computed by aggregating sectoral growth using the data Domar weights against the model Domar weights.

D.2 The Role of Individual Sectors in Comovement

We next address the question of whether some sectors systematically contribute more to aggregate comovement than others. Equation (2.2) can be written as $d \ln G_{n,t} = \sum_i d \ln \mathcal{V}_{ni,t}$, where $\mathcal{V}_{ni,t} \equiv \sum_{k=0}^{\infty} \sum_\ell s_{\ell ni,k} \theta_{\ell i,t-k}$ is the contribution of shocks in sector i anywhere in the world to GDP growth of country n (not to be confused with value added in sector i country n). The GDP covariance is simply additive in the covariances of sectoral $d \ln \mathcal{V}_{ni}$ with foreign GDP:

$$\rho_{nm} = \sum_i \frac{\text{Cov}(d \ln \mathcal{V}_{ni}, d \ln G_m)}{\sigma_n \sigma_m}. \tag{D.1}$$

Thus, we can decompose the overall GDP correlation into components due to shocks in individual sectors. Further, we can treat $d \ln \mathcal{V}_{ni}$ as its own "economy," and decompose its covariance with foreign GDP into shock correlation and transmission:

$$d \ln \mathcal{V}_{ni,t} = \underbrace{\sum_{k=0}^{\infty} s_{nni,k} \theta_{ni,t-k}}_{\mathcal{D}_{ni}} + \underbrace{\sum_{k=0}^{\infty} s_{mni,k} \theta_{mi,t-k}}_{\mathcal{P}_{ni}} + \underbrace{\sum_{k=0}^{\infty} \sum_{n' \neq n,m} s_{n'ni,k} \theta_{n'i,k}}_{\mathcal{T}_{ni}}. \tag{D.2}$$

$$\begin{aligned} \text{Cov}(d \ln \mathcal{V}_{ni}, d \ln G_m) \;=\; & \underbrace{\text{Cov}(\mathcal{D}_{ni}, \mathcal{D}_m)}_{\text{Shock Correlation due to } i} \\ & + \underbrace{\text{Cov}(\mathcal{D}_{ni}, \mathcal{P}_m) + \text{Cov}(\mathcal{P}_{ni}, \mathcal{D}_m) + \text{Cov}(\mathcal{P}_{ni}, \mathcal{P}_m)}_{\text{Bilateral Transmission due to } i} \\ & + \underbrace{\text{Cov}(\mathcal{D}_{ni} + \mathcal{P}_n + \mathcal{T}_{ni}, \mathcal{T}_m) + \text{Cov}(\mathcal{T}_{ni}, \mathcal{D}_m + \mathcal{P}_m)}_{\text{Multilateral Transmission due to } i}. \end{aligned} \tag{D.3}$$

This way, we can evaluate whether the contribution of sector i to GDP comovement is due primarily to sector i shocks being correlated across countries, or to the fact that shocks to i transmit across countries.

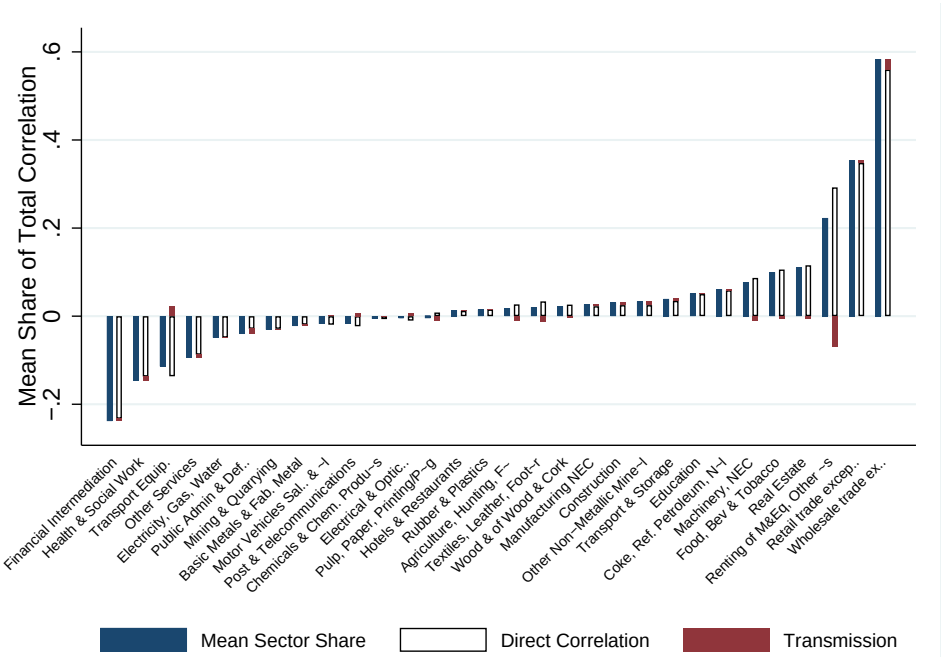
Figure A8 plots the results of this approach in our baseline model, averaging across countries for each sector. We express the terms in equation (D.3) relative to the aggregate correlation between countries n and m to interpret the results as shares. There is substantial heterogeneity in the average contributions of individual sectors to GDP comovement. Services sectors tend to be the most prominent, mirroring their relatively large size. The Wholesale and Retail Trade sectors are among the most important. Sectors like Financial Intermediation, Health and Social Work, and Transport Equipment contribute negatively to aggregate comovement. Even more so than our aggregate findings, the shock correlation term is predominant at sector level, and transmission is a small minority.

D.3 Correlation Structure of Shocks

We now investigate whether the recovered shocks have a factor structure. We begin by estimating a factor model featuring a global factor F_t^g, a country factor $F_t^m, \forall m \in N$ and a sector factor $F_t^i, \forall i \in J$ on the composite shocks $dZ_{mi,t}$ in the one-shock model:

$$\ln Z_{mi,t} = \gamma_{mi}^g F_t^g + \gamma_{mi}^i F_t^i + \gamma_{mi}^m F_t^m + u_{mi,t},$$

Figure A8: Mean Sectoral Shares in Aggregate GDP Correlations, G7, 1978-2007



Notes: This figure displays the average share of total bilateral correlation accounted for by each sector (blue bars), as well as the decomposition in equation (D.3) into the component due to the shock correlation (white bars) and bilateral+multilateral transmission (red bars), for G7 country pairs over the period 1978-2007.

where γ^g, γ^i and γ^m are the corresponding global, sector and country loadings. The assumption is that $\gamma^i_{mk} = 0, k \neq i$, and $\gamma^m_{ni} = 0, n \neq m$. We then compute variance decompositions of the shocks into components attributable to each type of factor. Note that the factor estimation does not impose that the factors are orthogonal, however in practice we found that the estimated factors were uncorrelated, making the variance decomposition straightforward.

Table A7 displays the mean (p25, p75) share of the variance attributable to each type of factor for the composite shock, as well as the four shocks extracted in the business cycle accounting extension in Section 5.2. Clearly, the common global factor does not explain much of the variance of the shocks, with the partial exception of the investment shock. A larger role is played by the country factors, and, to a lesser extent, sectoral factors. Overall, however, there is no clear dominant type of factor explaining the bulk of the variation in the extracted shocks. For all shocks except the investment shock, the three sets of factors on average explain less than 50% of the variance of the series. For the investment shocks, the three factors explain over 90% of the variation on average.

The second exercise we conduct is to regress the panel for each type of shock on country-time and sector-time fixed effects and compute the partial R^2 due to each type of fixed effects. This captures the variation absorbed by the country-time specific components and sector-time specific means. The results in Table A8 illustrate a similar pattern as with the estimated factors: with the exception of the investment shock, no fixed effects explain a majority of the variation for any shock. The sector-time effects play a somewhat larger role. For the investment shock, country-time effects are by far the dominant component.

In sum, our results suggest that common global factors are not the driving source of shock correlation, with the partial exception of the investment shock. Rather, common country-specific and (to a lesser extent) sector-specific components help generate the observed correlation patterns. However,

Table A7: Factor Decomposition of Shocks

Factor	Shock				
	$\ln Z_{mi,t}$	$\ln \xi^Z_{nj,t}$	$\ln \xi^H_{nj,t}$	$\ln \xi^X_{nj,t}$	$\ln \xi^I_{nj,t}$
Global	0.13	0.11	0.11	0.08	0.27
(p25, p75)	(0.01, 0.20)	(0.02, 0.16)	(0.01, 0.17)	(0.01, 0.12)	(0.23, 0.33)
Country	0.20	0.17	0.21	0.18	0.52
(p25, p75)	(0.05, 0.30)	(0.03, 0.25)	(0.04, 0.33)	(0.04, 0.29)	(0.46, 0.59)
Sector	0.13	0.13	0.13	0.12	0.10
(p25, p75)	(0.02, 0.22)	(0.02, 0.20)	(0.02, 0.18)	(0.02, 0.19)	(0.03, 0.16)

Note: This table reports the summary statistics for the shares of the variances accounted for by the factor in the row, for each type of shock in the column. Sample of 30 sectors for G7 countries from 1978-2007 as described in the text.

Table A8: Explanatory power of country-time and sector-time effects

Fixed Effects	Shock				
	$\ln Z_{mi,t}$	$\ln \xi^Z_{nj,t}$	$\ln \xi^H_{nj,t}$	$\ln \xi^X_{nj,t}$	$\ln \xi^I_{nj,t}$
Country-time	0.11	0.11	0.17	0.07	0.85
Sector-time	0.22	0.20	0.22	0.20	0.23

Note: This table presents the partial-R^2 of country-time and sector-time effects in a regression of a panel of a shock series on country-time and sector-time effects. Each column presents the results for one of the shock series considered in the paper. The sample is 30 sectors for the G7 countries between 1978-2007 as described in the text.

a substantial fraction of variation in the shocks is idiosyncratic.

Table A9 reports the sector-specific correlations of shocks. The first column averages the correlations of shocks within the same sector (for example, correlation of the textile sector in the US with the textile sector in the UK). The second column is the average of the cross-border correlations of different sectors (for example, correlation of the textile sector in the US with the machinery sector in the UK). There is indeed quite a bit of variation across sectors in these averages. The mean within-sector correlation is 0.11, but the range is between -0.01 and 0.376. Within-sector correlations tend to be higher than cross-sector correlations, which are lower on average and exhibit less range.

D.4 The Role of The Input Network

Our next counterfactual to understand the role of the input network studies whether trade in intermediate inputs and final goods amplifies GDP comovement. To assess this, we compute versions of the model in which trade in inputs and trade in final goods, respectively, are shut down. These scenarios are constructed as subsets of the full autarky scenario in Section 4.6.2, by reallocating only intermediate or final shares to domestic sources. Figure A9 presents the change in average GDP comovement for the G7 and all countries in these counterfactual scenarios.

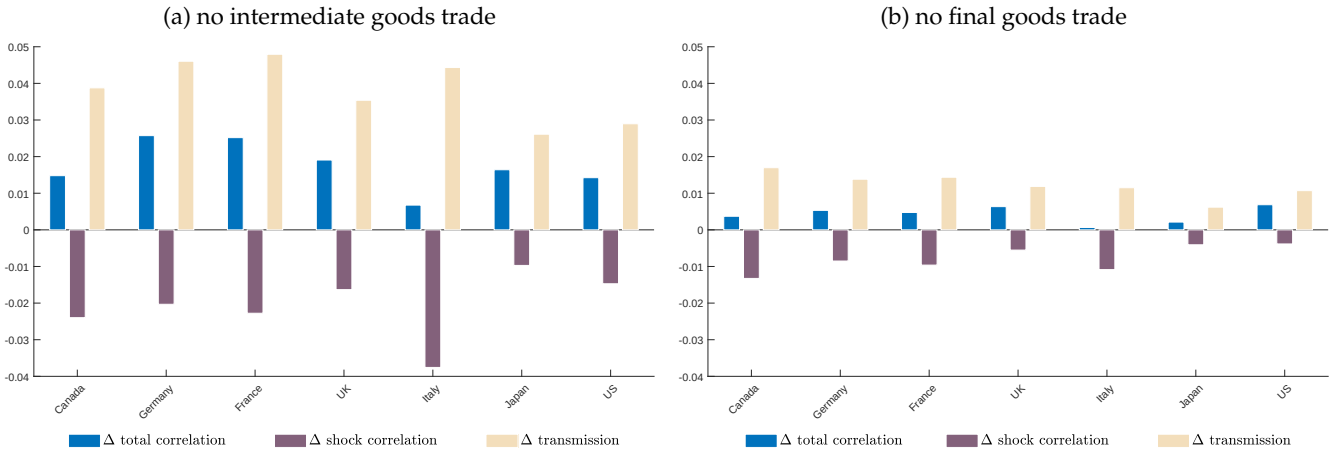
Table A9: Sector-Specific Shock Correlations

	Sector	Mean $\varrho^{Z}_{mj,nj}$	Mean $\varrho^{Z}_{mi,nj}$, $i \neq j$
AtB	agriculture hunting forestry and fishing	0.103	0.008
C	mining and quarrying	-0.013	0.027
D15t16	food beverages and tobacco	0.001	0.018
D17t19	textiles textile leather and footwear	0.169	0.049
D20	wood and of wood and cork	0.037	0.048
D21t22	pulp paper paper printing and publishing	0.195	0.069
D23	coke refined petroleum and nuclear fuel	-0.003	0.024
D24	chemicals and chemical products	0.168	0.054
D25	rubber and plastics	0.192	0.057
D26	other nonmetallic mineral	0.290	0.077
D27t28	basic metals and fabricated metal	0.196	0.063
D29	machinery nec	0.376	0.075
D30t33	electrical and optical equipment	0.357	0.083
D34t35	transport equipment	0.116	0.042
D36t37	manufacturing nec; recycling	0.053	0.054
E	electricity gas and water supply	0.173	0.026
F	construction	0.087	0.044
G50	sale maintenance and repair of motor vehicles	0.044	0.046
G51	wholesale trade and commission trade	0.064	0.049
G52	retail trade except of motor vehicles	0.003	0.034
H	hotels and restaurants	0.026	0.014
I60t63	transport and storage	0.212	0.072
I64	post and telecommunications	0.219	0.021
J	financial intermediation	0.034	0.023
K70	real estate activities	0.061	0.049
K71t74	renting of m&eq and other business activities	0.105	0.047
L	public admin and defense; compulsory social security	0.086	-0.016
M	education	0.050	-0.027
N	health and social work	0.031	-0.044
O	other community social and personal services	0.049	0.013
	mean	0.110	0.035
	min.	-0.013	-0.044
	max.	0.376	0.083

Note: This table reports the average correlations of shocks across countries. The first column reports the same-sector correlations. The second column reports the cross-sector correlations.

Overall, both intermediate and final trade increase comovement on average. The impact of intermediate input trade on synchronization is more than twice as large as the impact of final trade, on average. This is sensible, as input trade is governed by the lower substitution elasticity and thus transmission is stronger. The main results of the full autarky experiment in Section 4.6.2 carry over to these more limited changes in trade costs. In particular, the Δ Shock Correlation term is consistently negative in both scenarios.

Figure A9: Change in GDP Correlation between Trade and No Trade Models: Decomposition



Notes: Panel (a) displays the mean change in the GDP correlation going from no intermediate goods trade to observed trade (blue bars), decomposing it into the mean Δshock correlation$_{mn}$ (brown bars) and transmission terms (yellow bars). Panel (b) displays the mean change in the GDP correlation going from no final goods trade to observed trade (blue bars), decomposing it into the mean Δshock correlation$_{mn}$ (brown bars) and transmission terms (yellow bars).

D.5 The Trade-Comovement Relation

Table A10 reports the results of running the "standard" trade-comovement regression in our data and the network model. This is a regression of bilateral real GDP correlation on a measure of bilateral trade intensity. A long literature following Frankel and Rose (1998) tries to understand why economies that trade more display higher GDP comovement in the data. Input linkages have been suggested as an explanation for the trade-comovement puzzle in a number of papers (see for instance Kose and Yi, 2006; di Giovanni and Levchenko, 2010; Johnson, 2014). Quantitatively, however, models have trouble generating even the same order of magnitude as the empirical relationship (model coefficients are often <10% of their empirical counterparts).

When it comes to GDP correlations, our model matches perfectly the trade-comovement relationship found in the data, by virtue of matching GDP growth rates for each country-year. Columns (1)-(2) run the trade-comovement regression in the data, while columns (3)-(4) do the same in the model. Since each GDP correlation can be additively decomposed into the Shock Correlation and Transmission components, we can also run the trade comovement regressions with those as the dependent variables. This is done in columns (5)-(8). We implement this exercise on the model with 29 countries in Section 5.1 to increase the sample size. It turns out that trade intensity is correlated with both components of total GDP comovement. However, the bulk of the overall slope (0.73 out of 0.85) is accounted for by the positive relationship between trade intensity and shock correlation. This underscores the relevance of the Imbs (2004) critique of trade-comovement regressions: bilateral trade intensity can be a proxy of country similarity, and thus of correlated shocks.

D.6 Role of Financial Integration

This subsection explores an alternative international financial market structure. Whereas in the baseline countries are in financial autarky, we now extend the model to allow countries to trade a complete set of state-contingent securities. In this setting the goods prices also hinge on the financial flows across countries and the channels of international transmission are different.

Table A10: The Trade-Comovement Relation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Data		Model					
Dep. Var:	Bilateral GDP growth correlation				Shock correlation		Transmission	
Trade intensity (avg)	0.085***							
	(0.012)							
Trade intensity (1995)		0.086***						
		(0.011)						
Trade intensity (model, avg)			0.085***		0.073***		0.012***	
			(0.011)		(0.011)		(0.001)	
Trade intensity (model, 1995)				0.085***		0.073***		0.012***
				(0.011)		(0.011)		(0.001)
N	406	406	406	406	406	406	406	406

Notes: This table presents the results of a regression of bilateral GDP growth correlation on trade intensity for the data and in the 29-country model in Section 5.1. Trade intensity is defined as the sum of bilateral flows over the sum of the two countries' GDPs. The first row uses the average trade intensity over the 1995-2007 period, while the second row uses the initial intensity.

We make the following modifications relative to the baseline economy. First, we allow the period-utility to be non-GHH:

$$U\left(C_{n,t}, H_{n1,t}, \ldots, H_{nJ,t}\right) = \frac{C_{n,t}^{1-\sigma}}{1-\sigma} - \sum_{j} H_{nj,t}^{1+\frac{1}{\psi}},$$

where σ controls the wealth effects of international transfers. The flexibility to accommodate a wealth effect of flexible magnitude is important because the impact of the international financial transfers depends on it. Second, the budget constraint for consumers in country n is

$$\sum_{t}\sum_{s^t} P_{n,t}(s^t)C_{n,t}(s^t) = \sum_{t}\sum_{s^t}\left(\sum_{j} W_{nj,t}(s^t)H_{nj,t}(s^t) + \sum_{j} R_{nj,t}(s^t)K_{nj}\right),$$

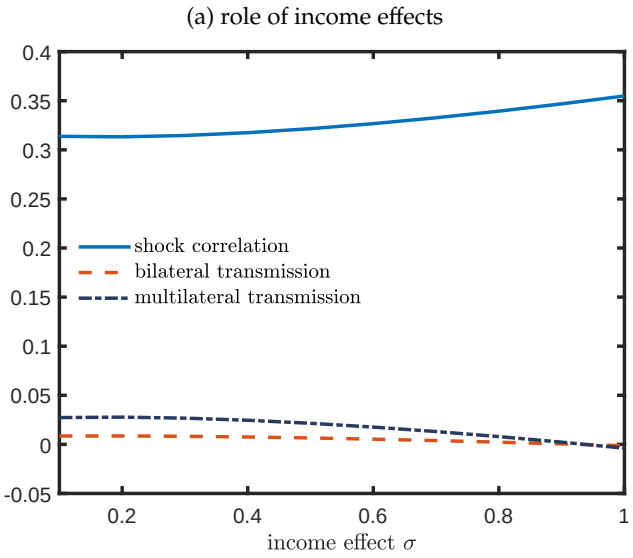
where s^t indexes histories of shocks up to time t. For simplicity we assume that the capital stock is fixed and focus on the impact response to shocks.

With complete markets, in all states, the marginal utility of 1 unit of nominal output across countries will be equalized, and the relative consumption and the real exchange rate move in the opposite directions (Backus and Smith, 1993):

$$-\sigma \ln C_{n,t} - \ln P_{n,t} = -\sigma \ln C_{m,t} - \ln P_{m,t}.$$

However, the insurance channel on the final goods consumption does not necessarily result in a stronger international transmission to measured real GDP. In fact, with complete markets, a positive TFP shock in country n directly induces an increase in country m's consumption, but it tends to lower country m's labor supply. At the same time, the magnitude the terms of trade response is dampened under complete markets as discussed in Heathcote and Perri (2002), which further low-

Figure A9: Correlated Shocks and Transmission with Financial Integration



Notes: This figure displays the average contributions of correlated shocks and transmission with different strengths of income effects in complete markets.

ers foreign firms' incentive to expand production capacity. These forces weaken the transmission of shocks from one country's real GDP to another. Figure A9 shows how the international comovement decomposition varies with σ. As expected, the shock correlations appear to be more important than our baseline economy. In the special case with $\sigma = 1$ and unitary elasticities of substitution, the relative goods prices remain constant in response to shocks, and the shock correlation will account for 100% of the international comovement, as we show analytically in Appendix B.1.

It is worth noting that the above results are only about how international financial integration in the form of complete markets affects the transmission of the real supply shocks that we focus on in this paper. They do not imply that global capital flows are not important in shaping international business cycle comovement. International financial integration in combination with imperfect asset markets can make room for shocks to the financial system that could be important sources of international comovement (Jordà et al., 2019; Miranda-Agrippino and Rey, 2020; Boehm and Kroner, 2023).

Table A11: Projecting Recovered Shocks on Identified Shocks

	TFP		Labor		Intermediate		Investment	
	R^2	Sig.	R^2	Sig.	R^2	Sig.	R^2	Sig.
Fernald TFP	0.09		0.00		0.01		0.01	
News	0.21	*	0.14	**	0.01		0.04	*
Sentiment	0.06		0.13		0.05	*	0.18	**
Monetary	0.06		0.04		0.05	**	0.06	
Fiscal	0.02		0.06	*	0.06		0.01	
Oil	0.06		0.03		0.01		0.15	***
Financial	0.03		0.11		0.02		0.25	
Uncertainty	0.20	*	0.13		0.10		0.20	
All together	0.54		0.51		0.32		0.58	

Notes: The columns labeled "R^2" report, for each recovered shock in the column, the R^2 from a bivariate regression of the growth in that shock on identified shocks in the row. The row "All together" reports the R^2 of regressing the shock in the column on all the externally identified shocks together. The column labeled "Sig." reports the level of significance of the category of identified shocks when all the identified shocks are used as regressors together in a multivariate regression. ***: significant at the 1% level; **: significant at the 5% level; *: significant at the 10% level. Variable definitions and sources are described in detail in the text.

D.7 Additional Exercises in the Four-Shock Model

Correlates of Recovered Shocks. We stress that the 4 shocks recovered in Section 5.2 use no external information or exogenous variation. Thus, they are consistent with a variety of microfoundations. To understand whether these recovered shocks correspond closely to existing independently identified shocks, we collect a number of shocks from earlier studies, and correlate them with each of our 4 recovered shocks. We make use of the following standard shock series: (i) the Fernald (2014) utilization-adjusted TFP; (ii) the Barsky and Sims (2011) news of future TFP; (iii) the Levchenko and Pandalai-Nayar (2020) sentiment shocks; (iv) the Romer and Romer (2004) monetary policy shocks, updated by Coibion et al. (2017); (v) federal spending (Ramey, 2011) and tax (Romer and Romer, 2010) shocks; (vi) oil price increases (Hamilton, 2003) and identified oil supply shocks (Baumeister and Hamilton, 2019); (vii) financial shocks proxied by excess bond premia (Gilchrist and Zakrajšek, 2012), and (viii) uncertainty shocks in the form of innovations to VIX (Bloom, 2009) and to the Baker-Bloom-Davis index of policy uncertainty. Many of these shocks come at monthly or quarterly frequency, and we convert them to annual frequency to match with our data.

Unfortunately, most of these identified shocks are specific to the US. The ideal exercise here would collect all possible independently identified shocks for all countries to determine which shocks are the most promising for explaining the patterns of comovement. To our knowledge, however, collections of these shocks do not exist for multiple countries. Thus, we can only compare these identified shocks to the annual series of shocks for the US recovered from our model. We have 30 years of observations. While this exercise will not speak directly to sources of cross-country comovement, it can at least tell us whether our recovered shocks correlate closely with externally identified shocks for one country.

We begin with regressing each model-recovered shock on an individual category of identified shocks. Table A11 reports the resulting R^2's. For TFP and labor market shocks, the Barsky-Sims news shocks have the highest bivariate explanatory power. Least explainable is the intermediate input shock, with the lowest overall R^2 and no set of identified shocks having an R^2 of over 0.06. By contrast, the investment shock appears to be the most correlated with other identified shocks, with sentiment, oil, financial, and uncertainty shocks having an R^2 of 15% or more.

Of course, the externally identified shocks themselves can be mutually correlated. To see which

identified shocks have the strongest conditional correlations with our recovered shocks, we regress the recovered shocks on all the identified shocks together. Note that with only 30 annual observations and 10 regressors, there are not that many degrees of freedom left. Nonetheless, columns labeled "Sig." report the level of significance of individual shocks when all are included in the same regression. There is some variation in which shocks are most important. Overall, news and sentiment shocks appear most correlated with our shocks, but their relative importance also varies across shocks. Fiscal, monetary, oil, and uncertainty shocks appear with varying levels of significance for individual series.

All in all, there is no clear pattern of correlation, whereby a recovered shock can be convincingly attributed predominantly to a particular externally identified shock. Nonetheless, this exercise suggests that at least for the US, our shocks bear some resemblance to prominent identified sources of business cycle fluctuations.

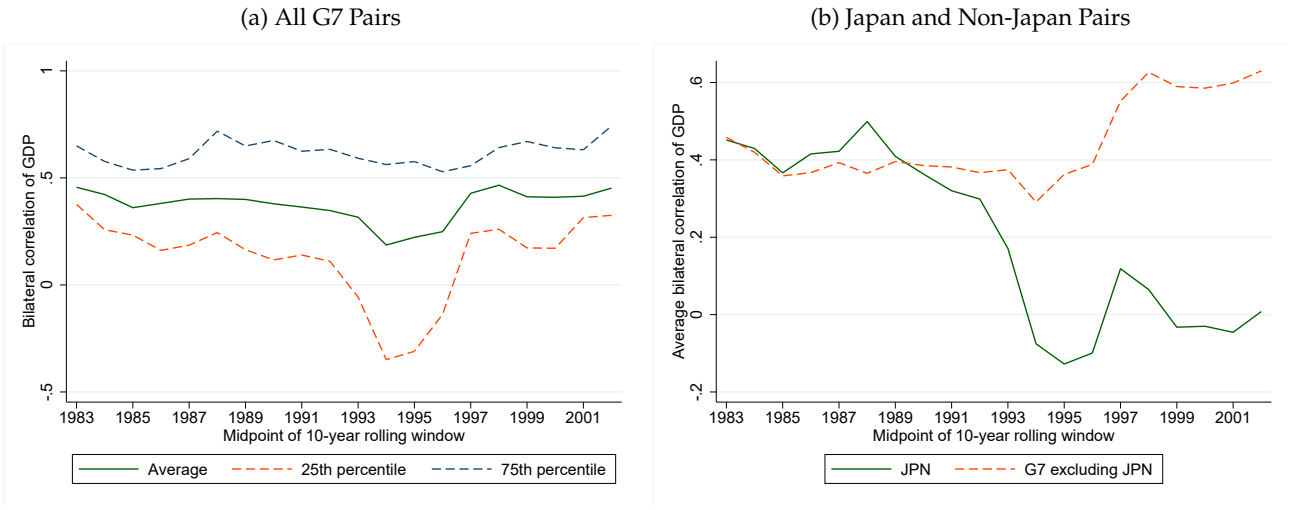
Historical Narrative. Unlike with recessions and expansions, of which there are typically several per country, average comovement does not exhibit large swings in our sample. There is a partial exception starting in the 90s, that we exploit to provide a historical narrative.

The left panel of Figure A10 plots the rolling 10-year average GDP correlation among the G7 countries over our sample period.[5] There is a dip in the mid-1990s, especially evident in the lower quartile. Digging into the country dimension, it turns out that the drop in the GDP correlation is driven by the decoupling of Japan from the rest of the G7 starting in about 1990. The right panel of Figure A10 plots the average rolling correlations for country pairs involving Japan and not involving Japan separately. The entire dip in the average correlations in the mid-1990s is driven by the fall in the correlations between Japan the the rest.

To investigate this further, Figure A11 plots the rolling 10-year correlation of GDP conditional on one shock at a time for Japan and non-Japan country pairs separately. It is clear that the most pronounced drop in the GDP correlations comes from the investment shock in particular. The pattern with the GDP coming from other shocks is less consistent. The labor shock-driven GDP also experiences a dip in correlation, but it is much milder and is mirrored by other countries' GDP correlations as well. The timing of the changes in the correlations driven by TFP and intermediate input shocks does not track the actual GDP correlation pattern. These findings are indeed consistent with the historical record. The Japanese stock market peaked on the last trading day of 1989, and proceeded to lose nearly 50% of its value over the course of 1990. That triggered the period known as "the Lost two Decades" in Japan. The stock market crash led to a recession in 1991-1993. This was followed by an even deeper recession in 1997-1998, that the rest of the G7 entirely missed. In 1997-98 Japan also experienced a banking crisis that took many years to resolve. (See Ito and Hoshi, 2020, ch. 14, for a narrative of the Japanese macroeconomy over this period.) The widespread "zombie banks lending to zombie firms" phenomenon led to a long-running malaise in the banking sector, characterized by under-capitalization and anemic lending to productive projects (Hoshi and Kashyap, 2004). Finally, in early 1999 Japan entered a zero-lower-bound period, alone at that time among the countries in our sample. All in all, this historical narrative is consistent with both Japan's overall decoupling from the rest of the G7 starting in the early 1990s, and with the investment shock being the primary proximate driver of that decoupling.

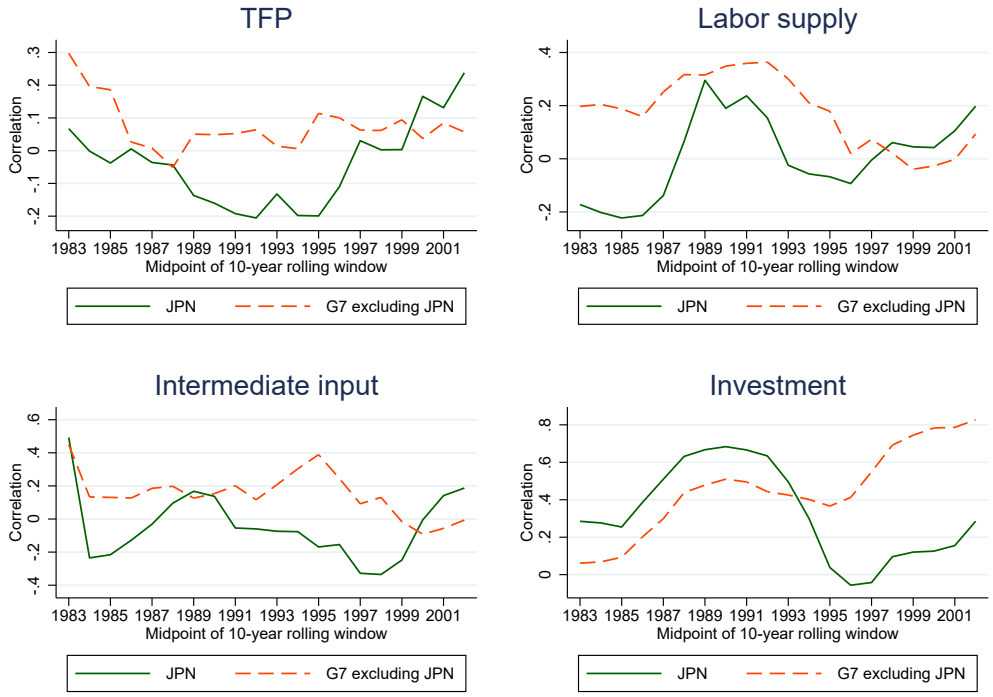
[5] This average correlation shows no discernible long-run trend between 1978 and 2007. Our follow-up work (Bonadio et al., 2021) is dedicated to understanding this lack of trend in spite of the large increase in trade openness over this period.

Figure A10: Average Rolling GDP Correlations, G7



Notes: Panel (a) displays the average rolling 10-year GDP correlations and the 25th and 75th percentile rolling 10-year GDP correlations for all G7 country pairs. Panel (b) displays the average rolling 10-year GDP correlations separately for country pairs involving Japan and not involving Japan.

Figure A11: Rolling GDP Correlations, Conditional on One Shock, G7



Notes: This figure displays the average rolling 10-year GDP correlations conditional on one shock at a time. Solid lines display country pairs involving Japan, dashed lines display all other G7 country pairs.

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