Complexity, Centralities, Roles
The case of the world trade network

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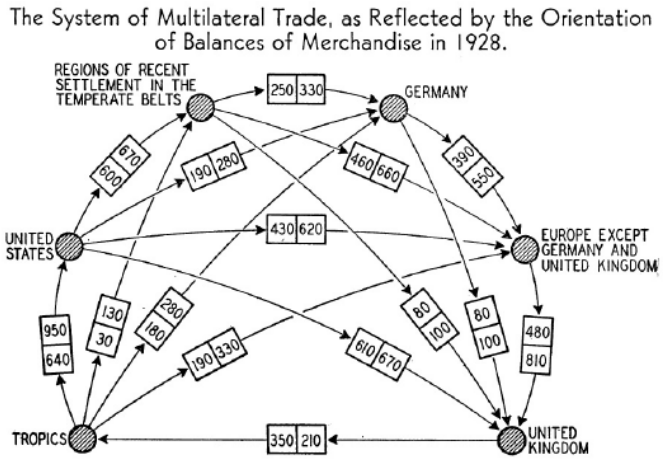
1. Introducing the International (World) Trade Network

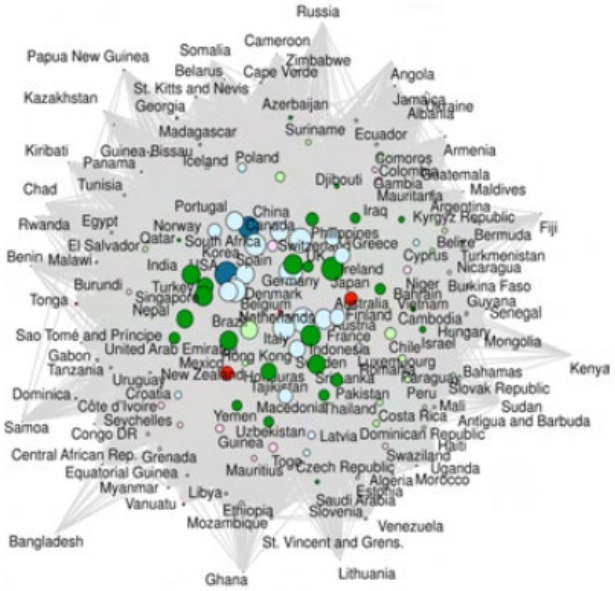
Data, definitions and properties

Economic transactions (between individuals, companies, countries) create links: networks are the most natural models.

Trade between countries: the International (or World) Trade Network (ITN, or WTN)



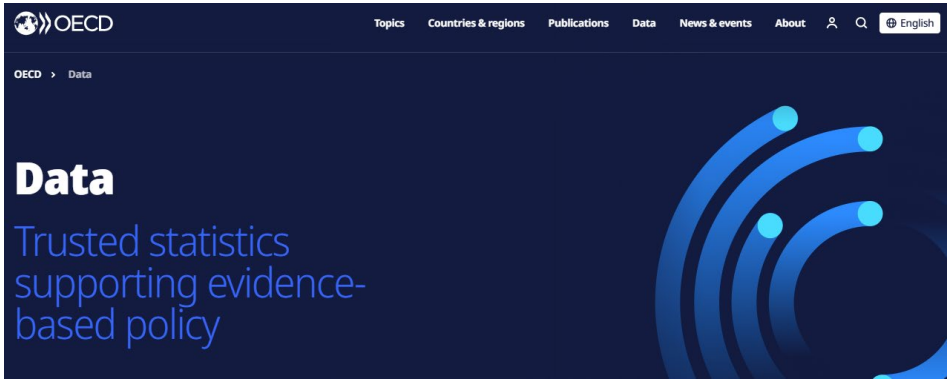
from Hilgerdt, Amer Econ Rev 1943



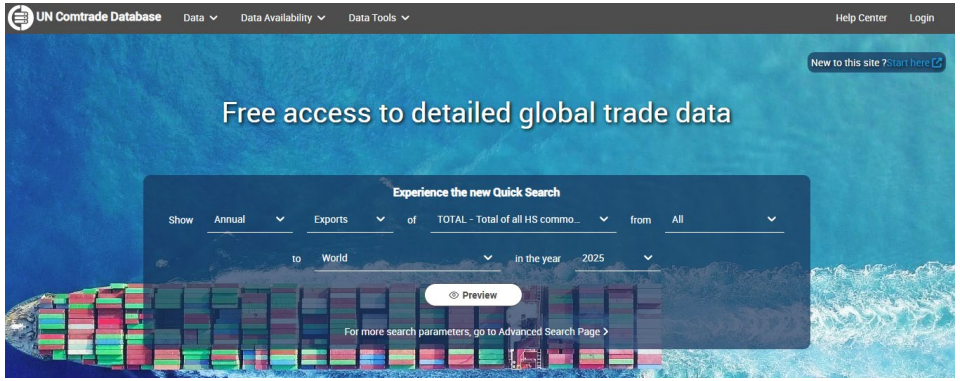
the WTN in year 2000

from De Benedictis and Tajoli, World Econ 2011

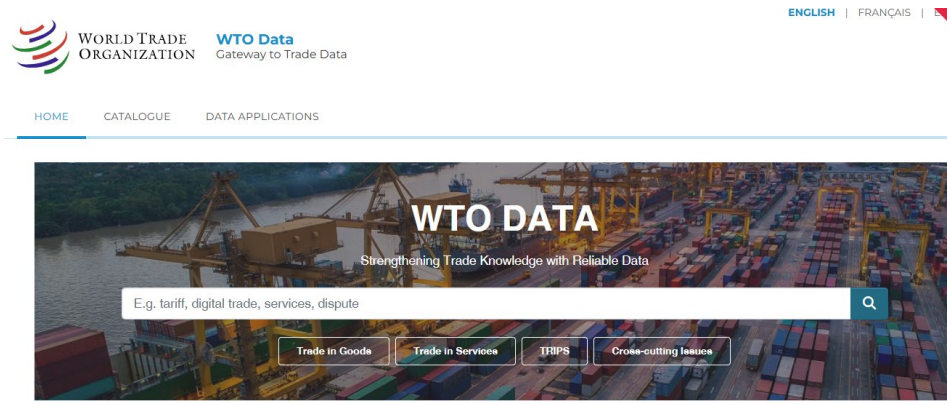
Multiple repositories for datasets:



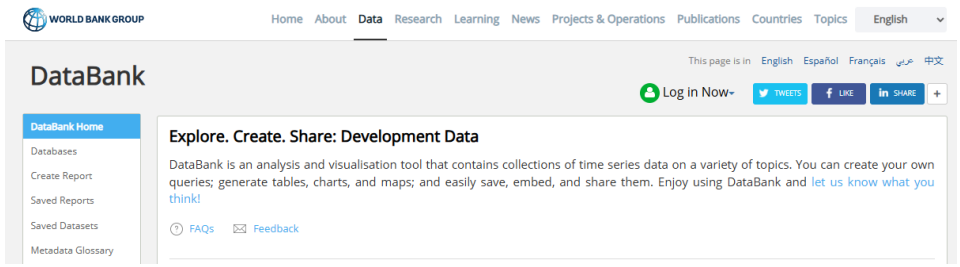
OECD https://www.oecd.org/en/data.html



UN-Comtrade https://comtradeplus.un.org/



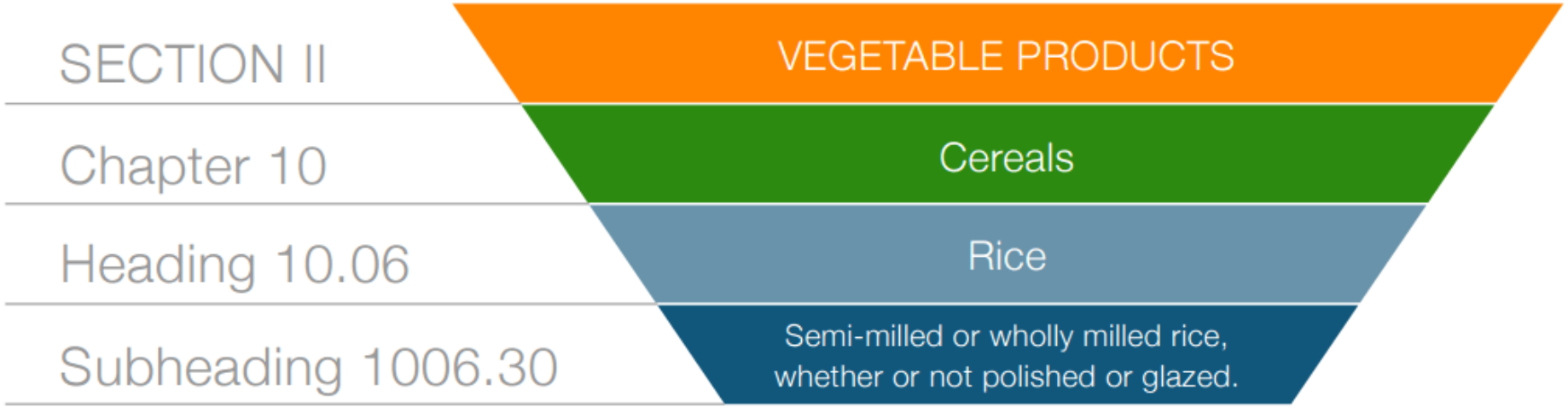
WTO https://data.wto.org/



World Bank https://databank.worldbank.org/

Data is mostly organized on a yearly basis.

Products classification: the Harmonized System (HS)



from en.wikipedia.org

Products are hierarchically partitioned into finer subsets:

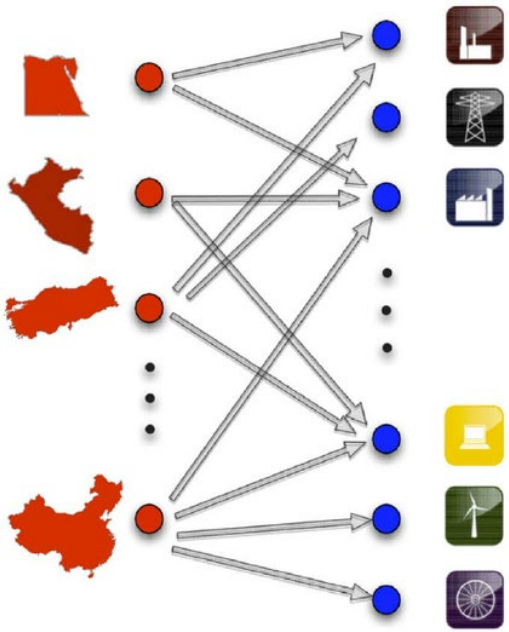
21 sections
⇒ 97 chapters (2-digit code)
⇒ 1,200+ headings (4-digit code)
⇒ 5,000+ sub-headings (6-digit code)

NETWORK MODELS

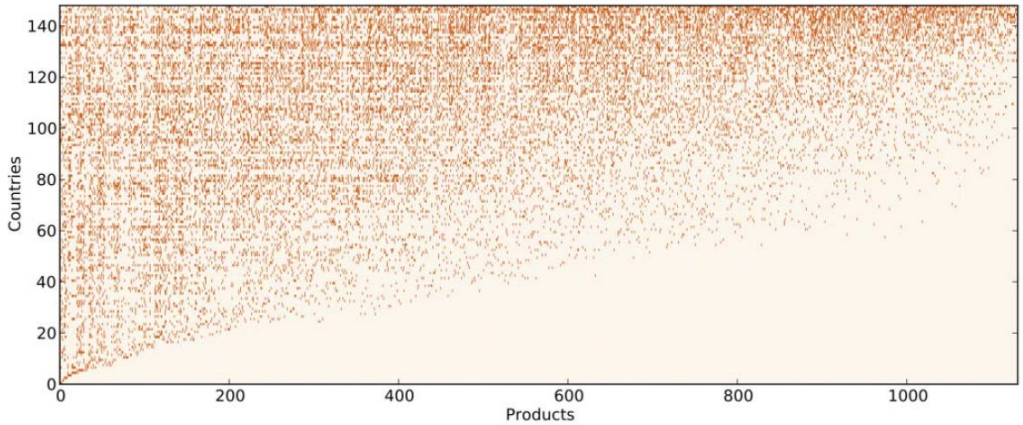
(binary, weighted, directed, bipartite, temporal, multilayer, higher-order networks…)

At fixed time (=year), the most used models are:

- Country-Product bipartite ("two-mode") network: *Which countries export which products (and how much)?*



from Caldarelli et al, Plos One 2012



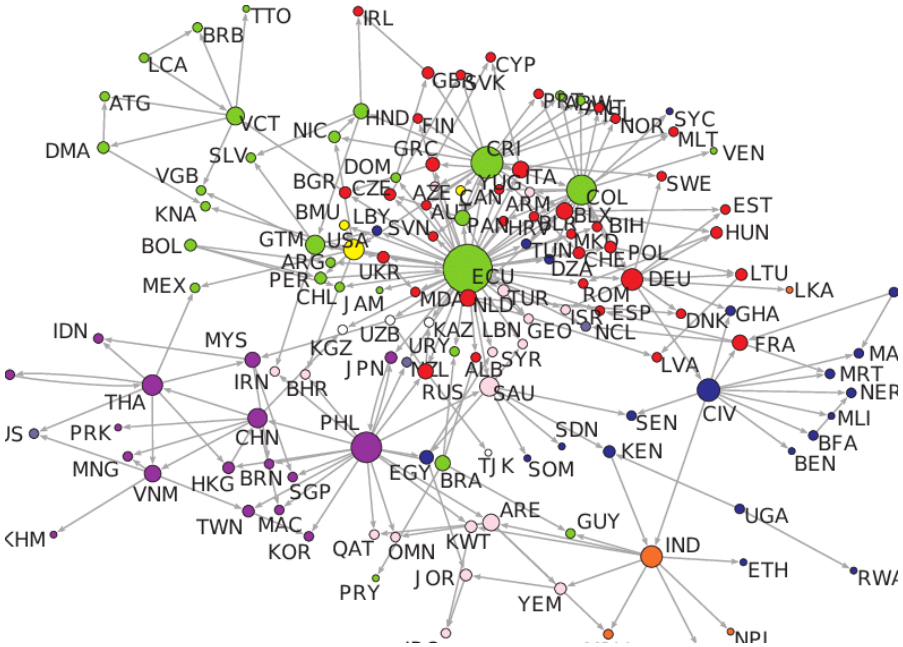
$M = [m_{cp}]$: binarized trade matrix,

$m_{cp} = 1$ if $r_{cp} > 1$ (Revealed Comparative Advantage)

$E = [e_{cp}]$: trade matrix,

export (USD) of product p from country c

- Country-to-Country ("one-mode") network: *Which countries j import product p exported by country i (and how much)?*



the trade network of bananas
from De Benedictis et al, Global Econ J 2014

Binary (directed) network:

$a_{ij} = 1$ if country i exports product p to country j,
$a_{ij} = 0$ otherwise

Weighted (directed) network:

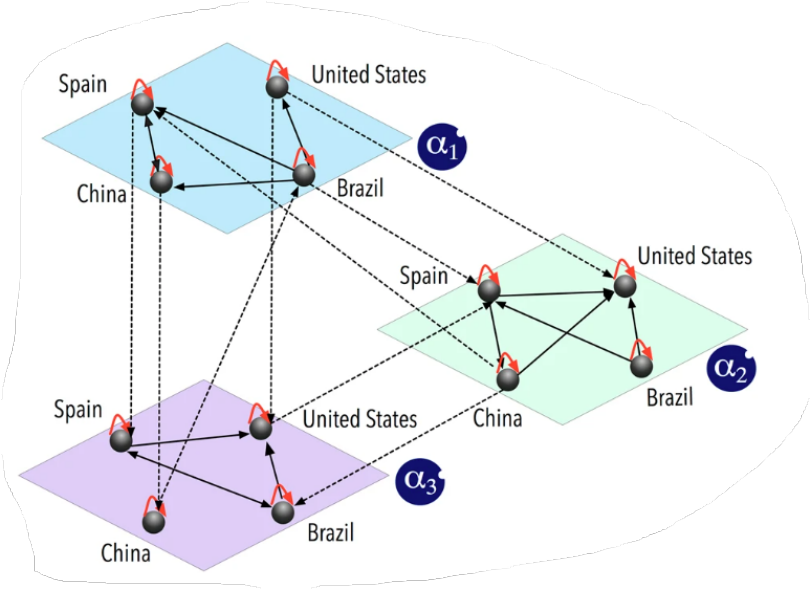
$w_{ij} \geq 0$ is the export (USD) of product p from country i to country j

The aggregate WTN (often simply "the WTN"):

$w_{ij} \geq 0$ is the export (USD) of *all* products from country i to country j

- Inter-Country Input-Output (ICIO) network: data are organized by countries and "industries" (i.e. economic sectors):

$w_{ih,jk} \geq 0$ is the export (USD) from industry h of country i, to industry k of country j (e.g. from China/electronics to US/motor-vehicles)



from Alves et al, Sci Rep 2019

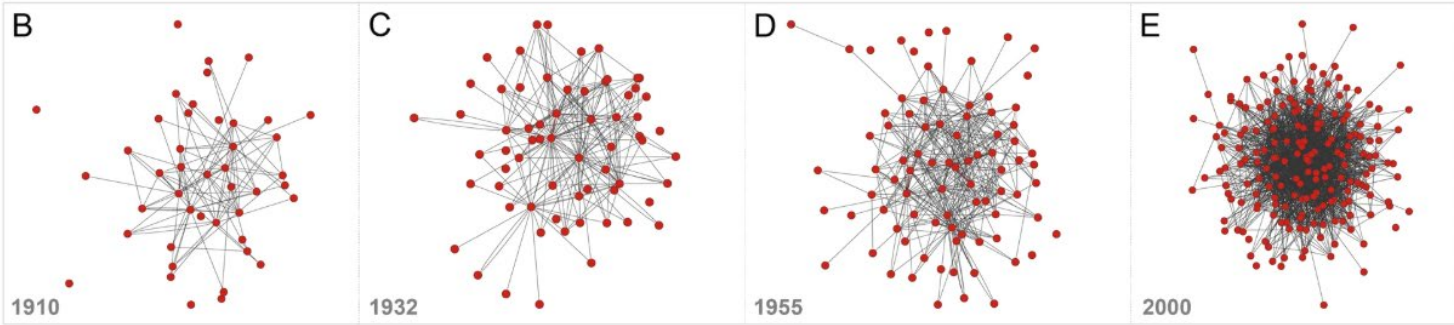
Data defines a multi-layer network (layer=industry or layer=country).

"Ordinary" (one-layer) networks are recovered by:

- aggregating all industries (nodes = countries) or all countries (nodes = industries)
- restricting to single countries (all industries) or single industries (all countries)

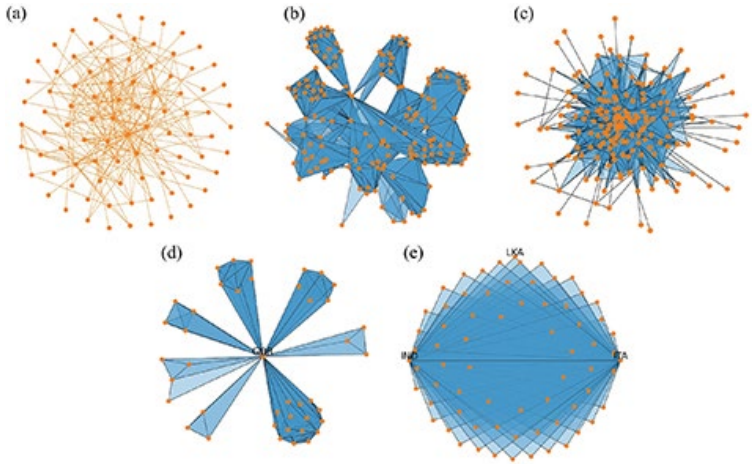
These datasets form the basis of the study of Global Value Chains (GVCs).

The 1-year discretization in data availability naturally defines the WTN as a time-varying network:



from Porfirio et al, Palgrave Commun 2018

More complex models include higher-order networks (simplicial complexes):



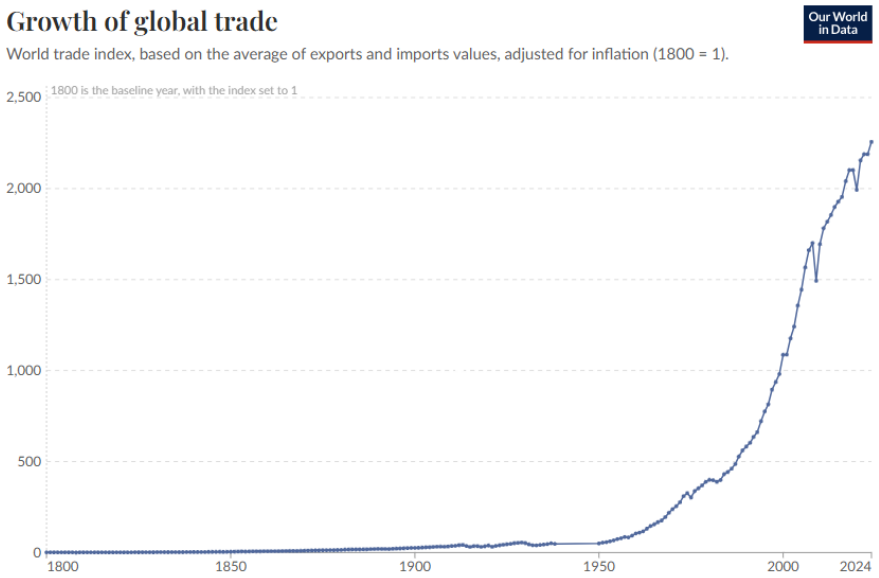
Higher-order interactions model "multilateral trade agreements"

from Ren et al, New J. Phys. 2024

Analysing the World Trade Network (in any of the previous forms) includes:

- assessing fundamental properties (e.g. global network indicators)
- classifying countries and products (centralities and roles)
- discovering mesoscale structures (communities and core-periphery)
- measuring the complexity of countries and products and their relations with network topology
- unveiling the structure and properties of Global Value Chains
- studying dynamical processes (e.g. business cycles, shock propagation)

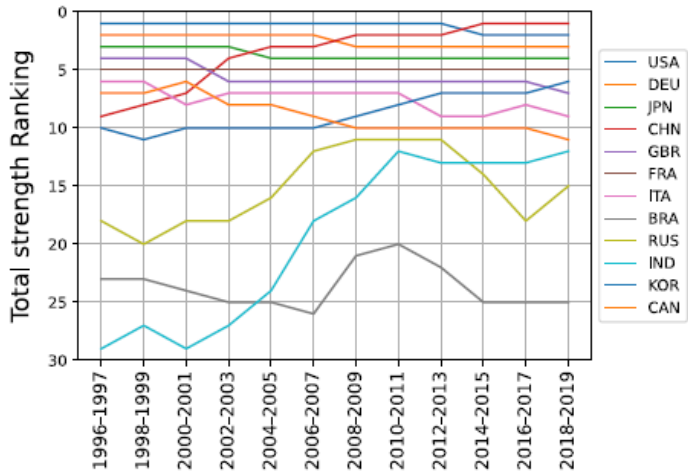
CHARACTERIZING THE WTN: BASIC FEATURES



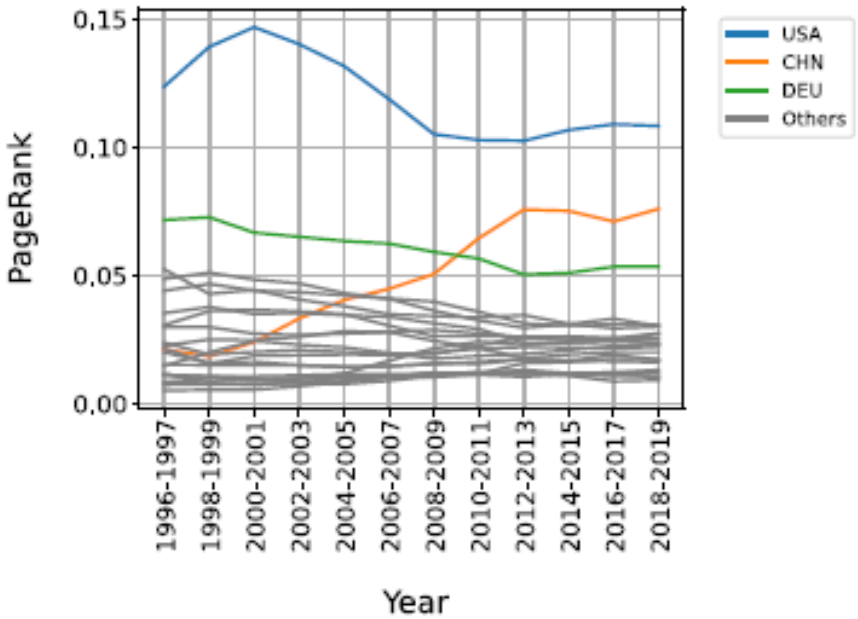
from OurWorldinData.org

The increasing trend in global trade value slows down and becomes irregular after the 2008 crisis.

China becomes the leading country in 2014/2015 in total import + export…

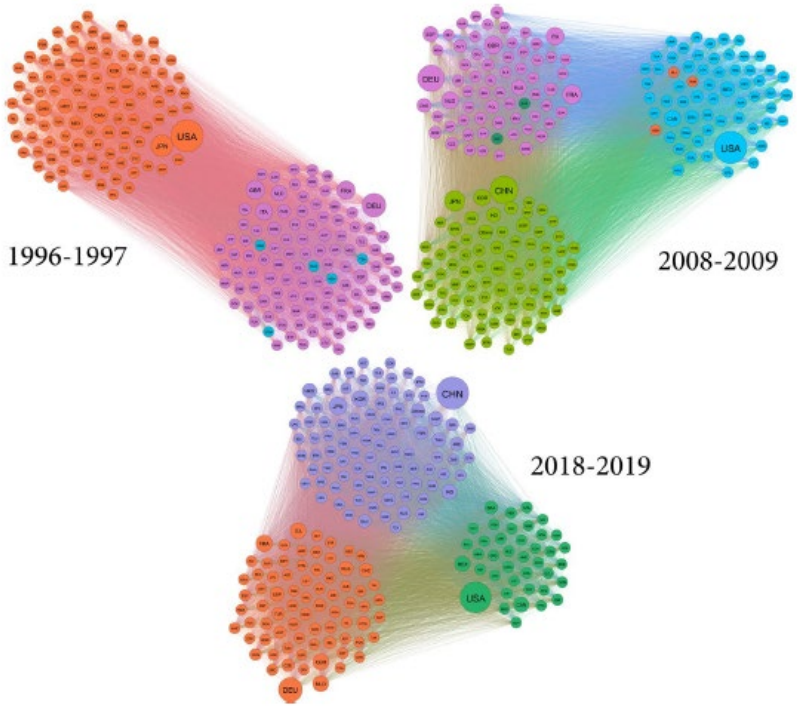


from Hoang et al, Appl. Netw. Sci. 2023

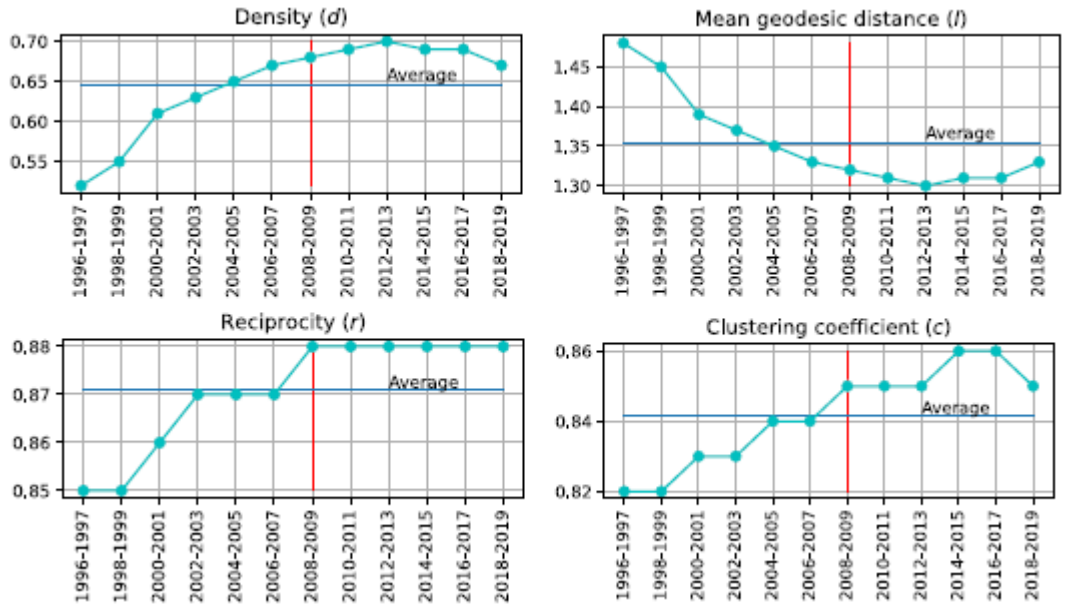


…but US remain by far the central country – if measured by PageRank.

Community detection confirms the transition from a bipolar (US-DEU) structure in the 90's to a tripolar structure (US-CHN-DEU) in the 10's.

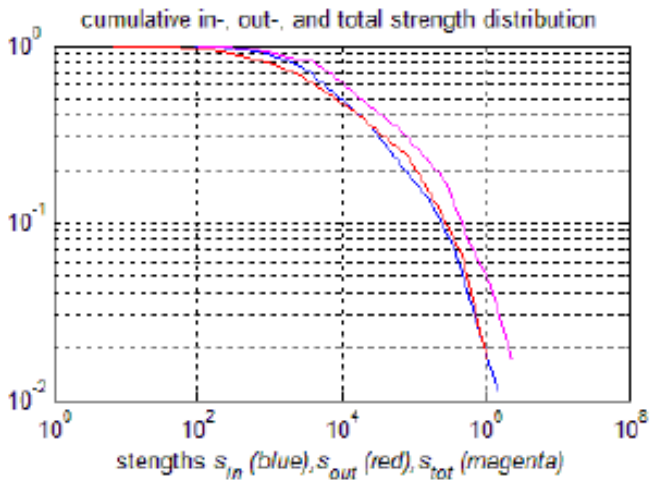


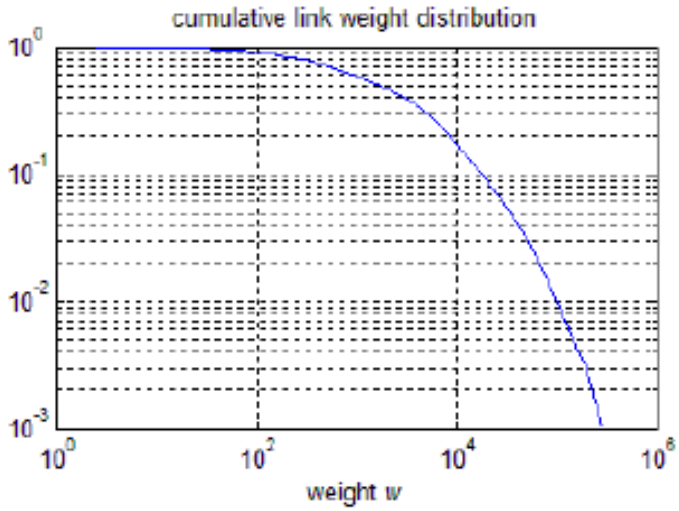
from Hoang et al, Appl. Netw. Sci. 2023



Until 2012, the WTN becomes increasingly dense and connected.

Node strengths and edge weights span many orders of magnitude ("multiscale" weighted network)
[2008 WTN data]

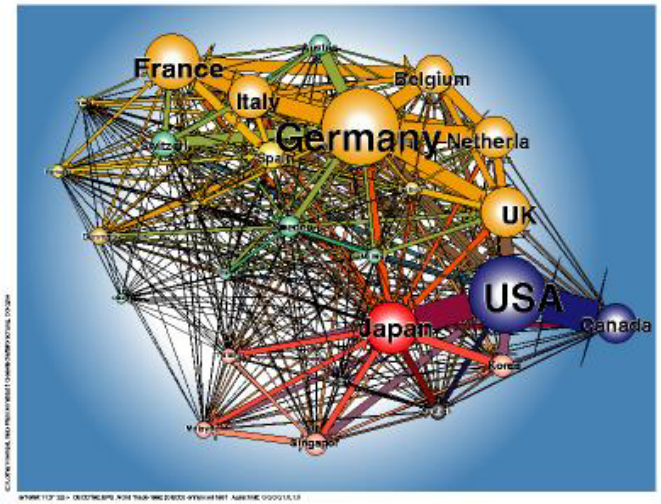




2. Complexity, centralization and fragility

[C. Piccardi and L. Tajoli, Complexity, centralization, and fragility in economic networks, PLoS ONE, 13(11), e0208265, 2018]

How fragile is the world economy?



from www.mpi-fg-koeln.mpg.de

Given the increasing globalization of economic systems, will economic shocks have widespread diffusion to all countries?

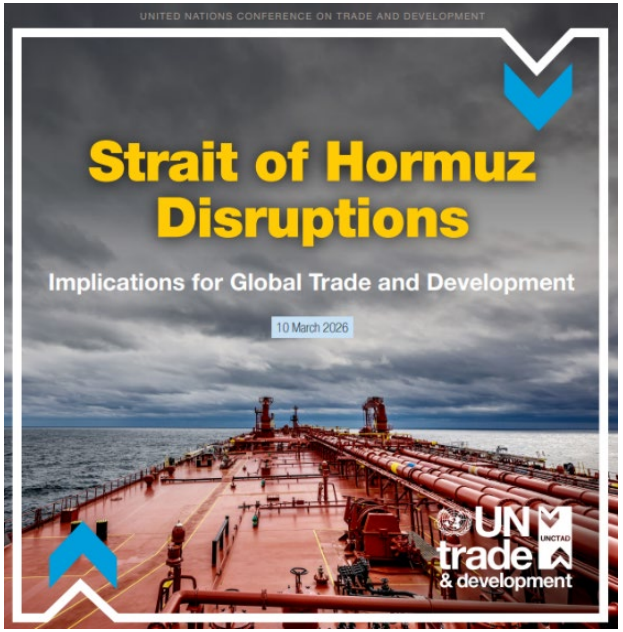
Two contrasting effects of the densification:

- Diversification, averaging effects, more resilience
- More connections, more effective shock propagation

The international financial crisis (2007-2008), the European debt crisis (2009-2010), the Covid-19 crisis (2020-2022), and the most recent crisis (Ukraine, Suez, Hormuz, etc.) suggest that indeed most of the world countries are highly exposed.

Focus on the broad (economic) impact of localized (non-economic) events:

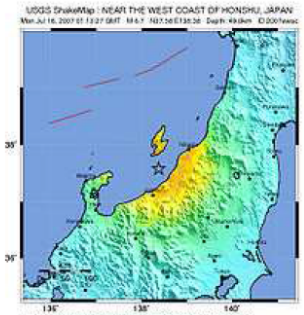
Strait of Hormuz crisis (2026)



Red Sea crisis (2024)

Japan earthquake (2007)

We analyzed the effect of business network damaged by an earthquake of July 16th, 2007.



Magnitude 6.6, not very big .

But it has huge impact on the economy.

All Japanese car makers (Toyota, Honda, Nissan, Matsuda, Mitsubishi...) stopped their production lines for about a week.

It causes a loss of 130,000 car production (=3 billion US dollars)

This was due to a breakdown of a small factory called "Riken" producing "piston rings"

Riken is the leading company

50% share in Japan

20% in the world

Very high-tech

Riken is an indispensable company. No alternative company to make such high quality piston rings for luxury cars.

No body paid attention to such a local company before the earthquake

Misako Takayasu,
plenary talk @ CCS 2016, Amsterdam

We focus on product trade networks and explore the relationship between product complexity and network centralization.

Research question:

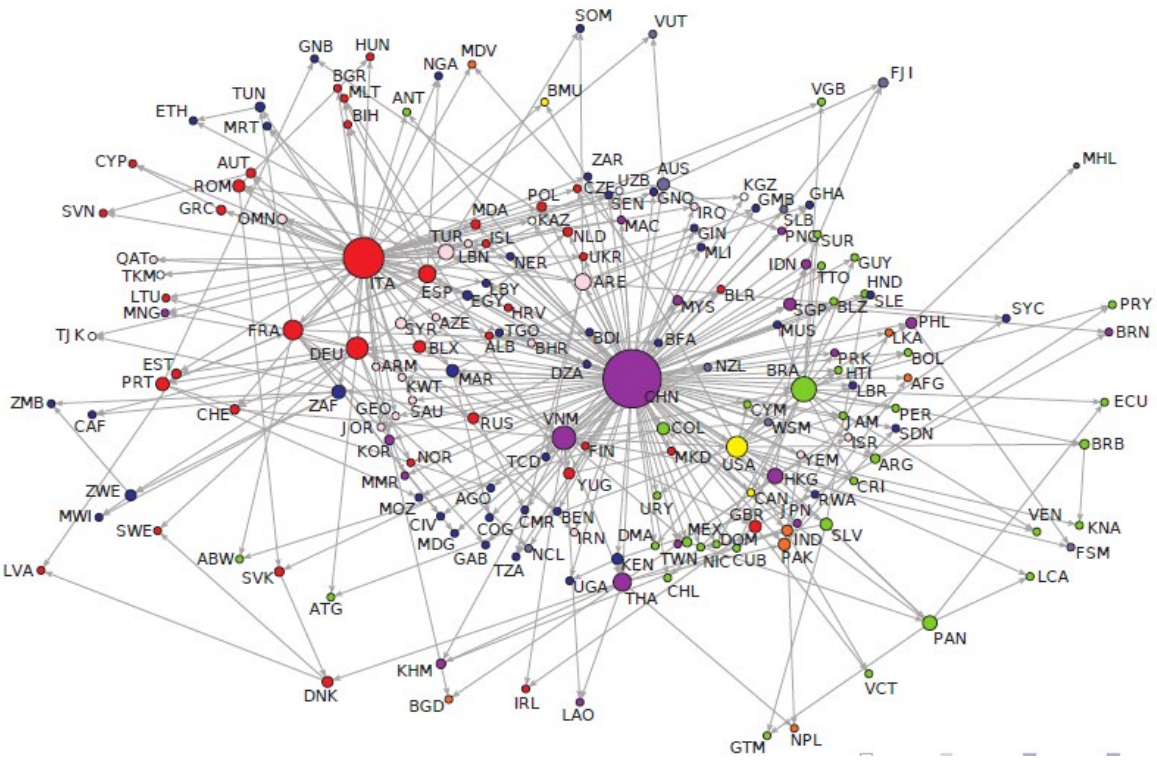
Are complex (high-tech) products distributed through centralized (hence more fragile) networks?

DATA

- Country-to-country trade (year 2014), 223 countries (CEPII-BACI database).
- HS 4-digit classification (1,242 products, partitioned into 15 Sections).

Examples:

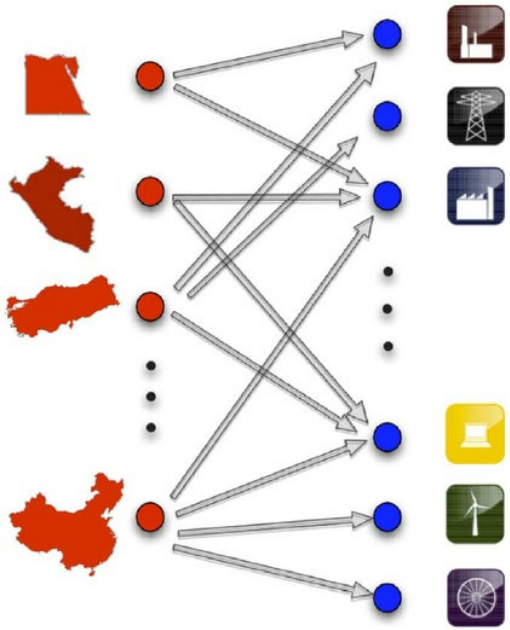
- Products #1211: "Plants and parts of plants, including seeds and fruits" (Section "Vegetable Products")
- Product #8513: "Portable electric lamps designed to function by their own source of energy" (Section "Machinery/Electrical")



the trade network of footwear
from De Benedictis et al, Global Econ J 2014

MEASURING PRODUCT COMPLEXITY

Aggregating data: the Country-Product bipartite ("two-mode") network



from Caldarelli et al, Plos One 2012

$E = [e_{cp}]$: trade matrix,
export (USD) of product p from country c

$M = [m_{cp}]$: binarized trade matrix,
$m_{cp} = 1$ if $r_{cp} > 1$
(Revealed Comparative Advantage)

"Traditional" measures:

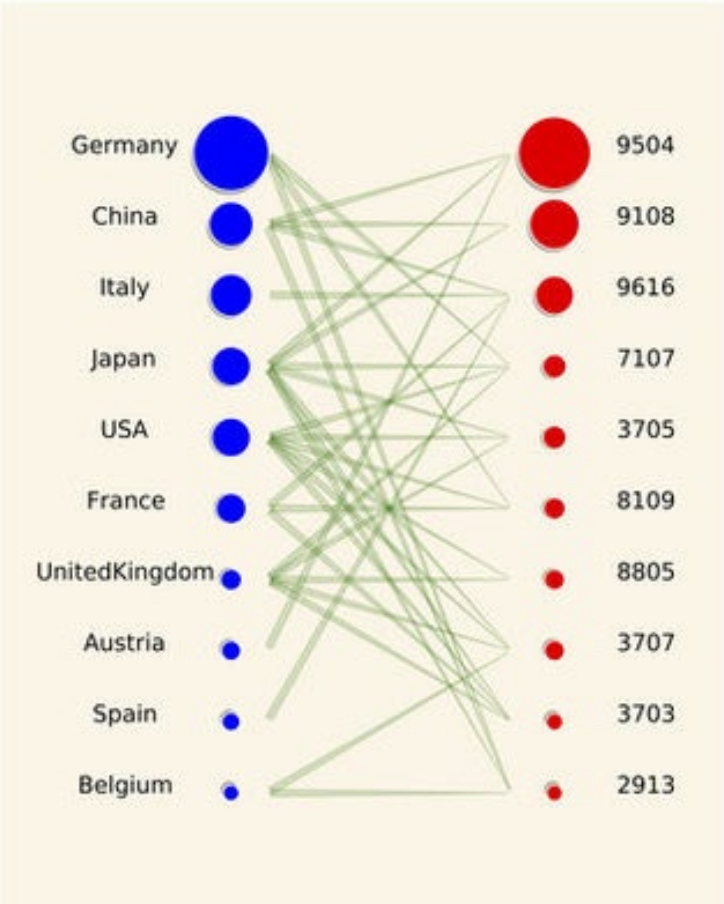
- (PRODY) The complexity of product p is the (weighted) average wealth of the countries exporting that product:

$$PRODY_p = \sum_c \frac{s_{cp}}{\sum_{c'} s_{c'p}} I_c$$

s_{cp}: share of product p in the export basket of country c;
I_c: GDP per capita (adjusted by PPP) of country c.

"Modern" measures:

- (HH - Hidalgo and Hausmann, 2009): an iterative algorithm ("method of reflections") simultaneously defines product and countries complexity *("the complexity of a product is the average of the complexities of the countries exporting it")*.

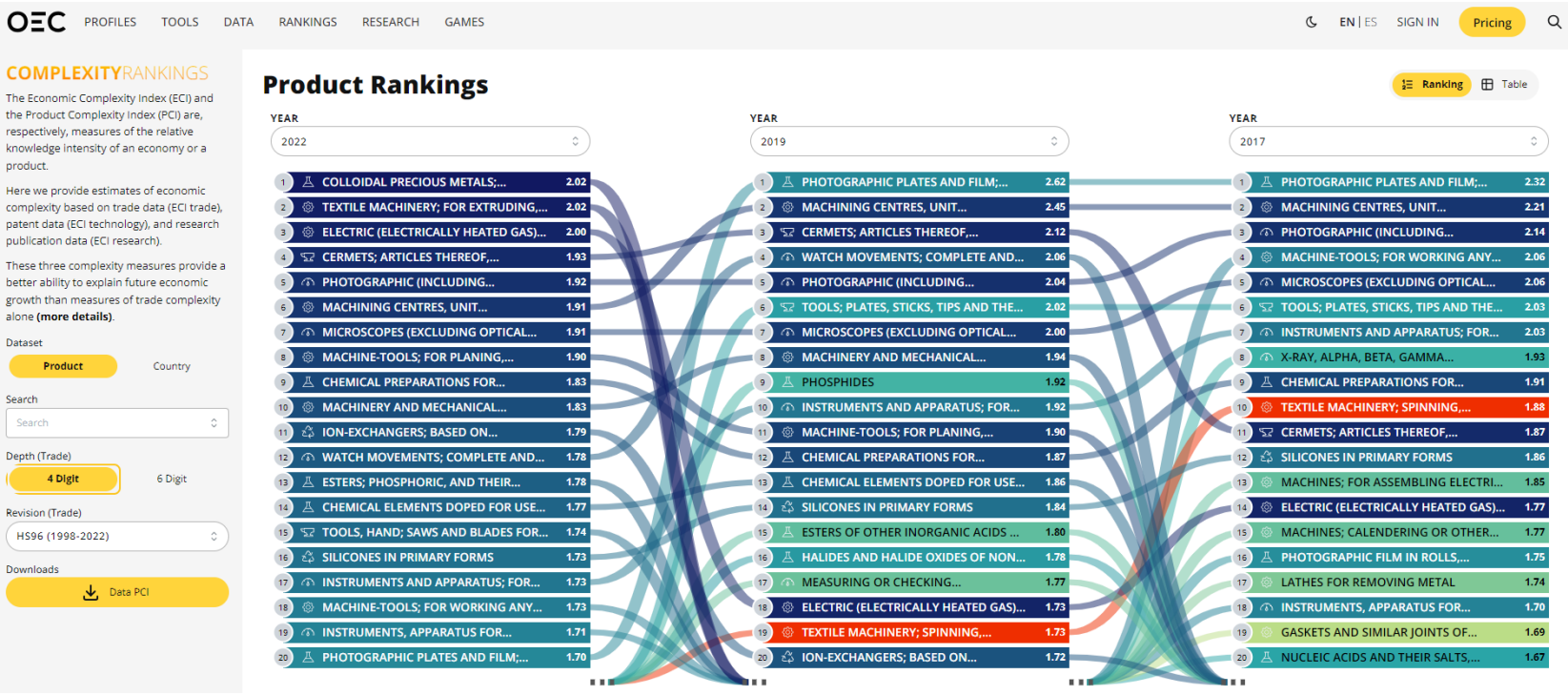


$$k_c^{(n)} = \frac{1}{k_c^{(0)}} \sum_p m_{cp} k_p^{(n-1)}$$

$$k_p^{(n)} = \frac{1}{k_p^{(0)}} \sum_c m_{cp} k_c^{(n-1)}$$

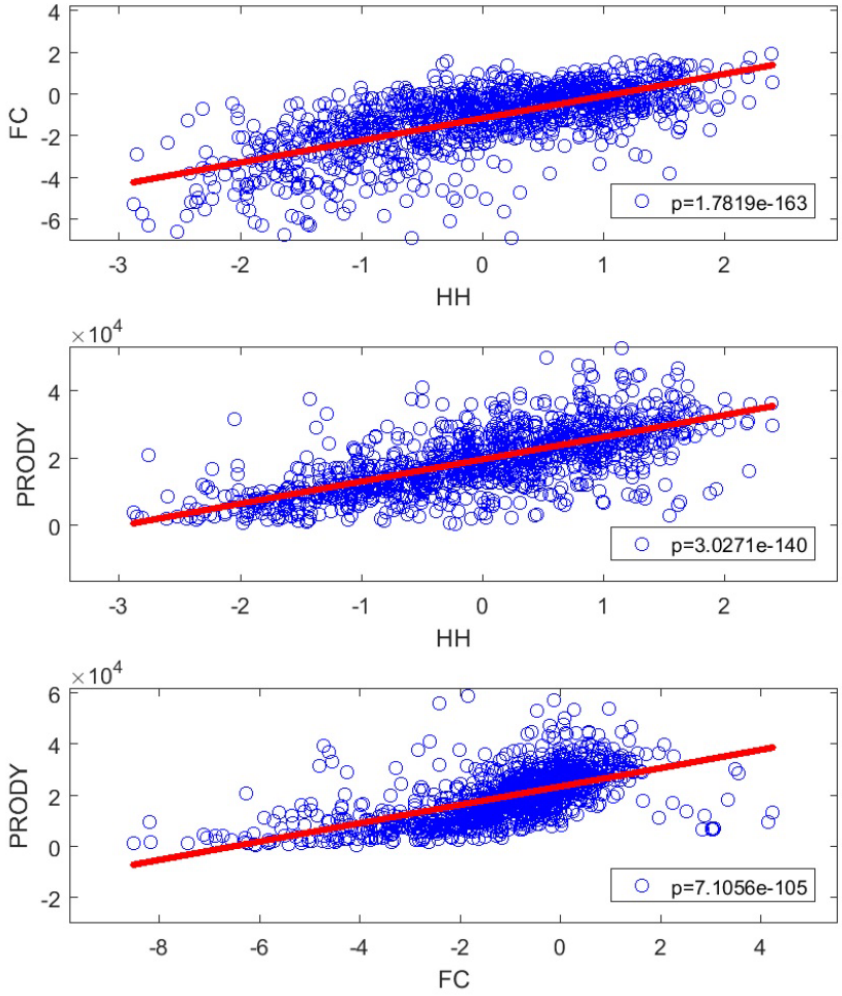
Rationale: Complex goods require many specific skills and inputs to be produced: their complexity can be assessed looking at the characteristics of the countries able to produce them.

Complexity values are available in a website ("the Observatory of Economic Complexity") updated yearly:



from oec.world

- (FC - Fitness/Complexity, Tacchella et al 2012): a nonlinear modification of the above HH iterative algorithm, to solve some conceptual problems.

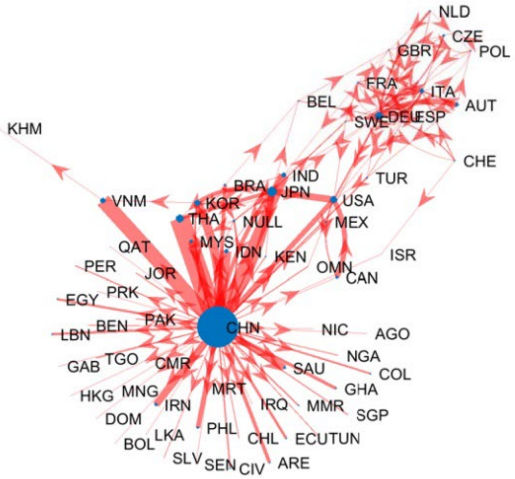


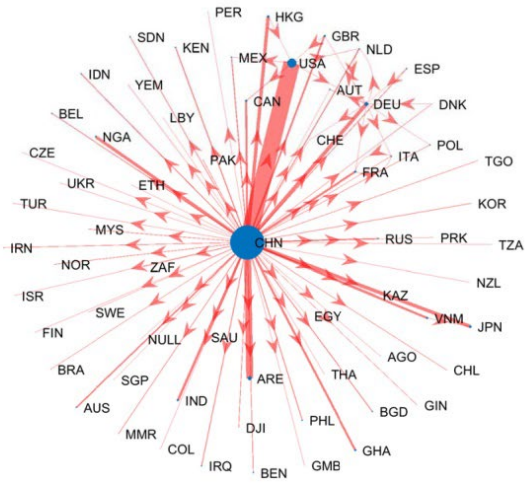
FC, HH, PRODY are highly correlated – yet remarkable differences exist for several products.

MEASURING NETWORK CENTRALIZATION

A gallery of product world trade networks:

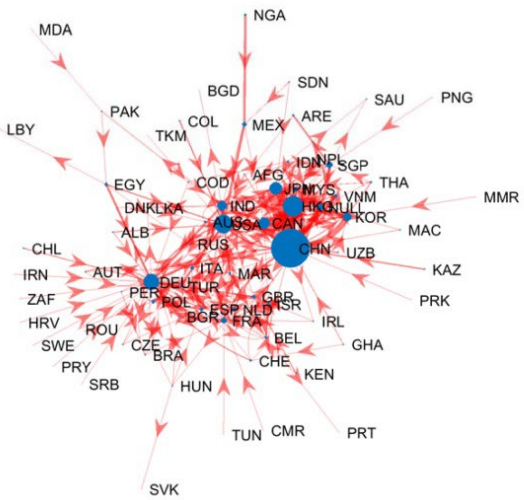
#7227
(Metal)

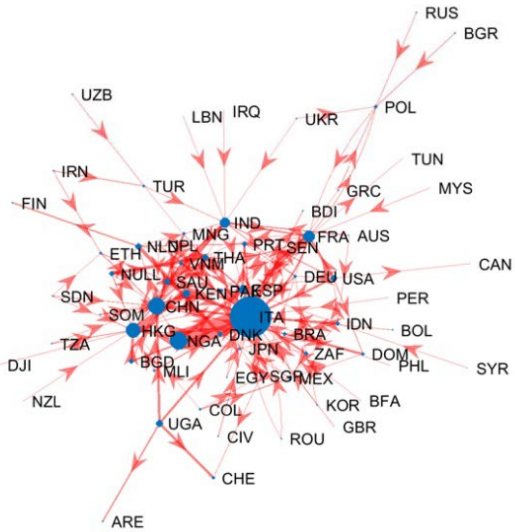




#8513
(Machin./Electr.)

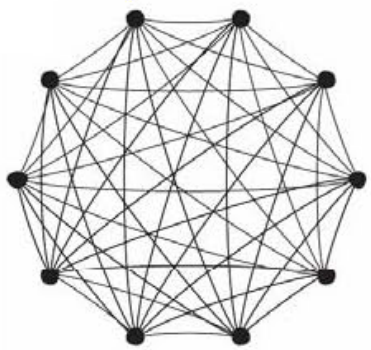
#1211
(Vegetable Prod.)



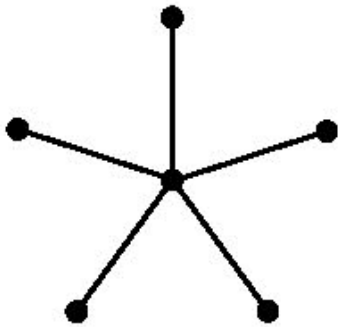


#4106
(Raw Hides,
Skins, etc)

We want to capture – product by product - the centralization of the world trade network topology:



vs



centralization = 0 centralization = 1

We use three indicators – related to topology, dynamics, and robustness.

GINI index: it directly measures export heterogeneity:

- Re-order nodes (=countries) by increasing out-strength (=export) $s_i = \sum_j w_{ij}$:

$$s_1 \leq s_2 \leq \cdots \leq s_n$$

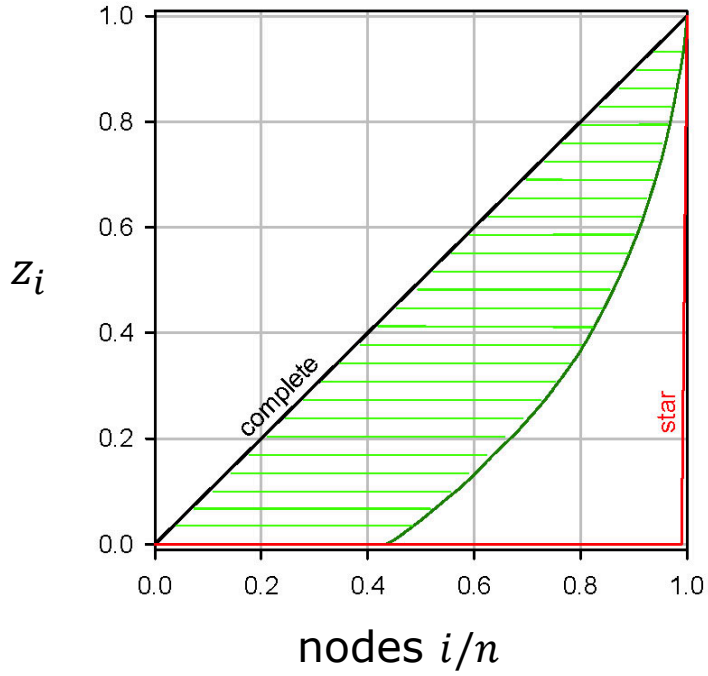
- Define the Lorenz (cumulated) curve as

$$z_1 = s_1/S \quad , \qquad z_2 = (s_1 + s_2)/S \quad , \qquad z_3 = (s_1 + s_2 + s_3)/S \quad , \qquad \cdots$$

where $S = \sum_i s_i = \sum_{ij} w_{ij}$ is the total world export.

GINI is the ([0,1]-normalized) green area.

GINI index = 0: all countries have the same exports.
GINI index = 1: the exports are concentrated in one single country.

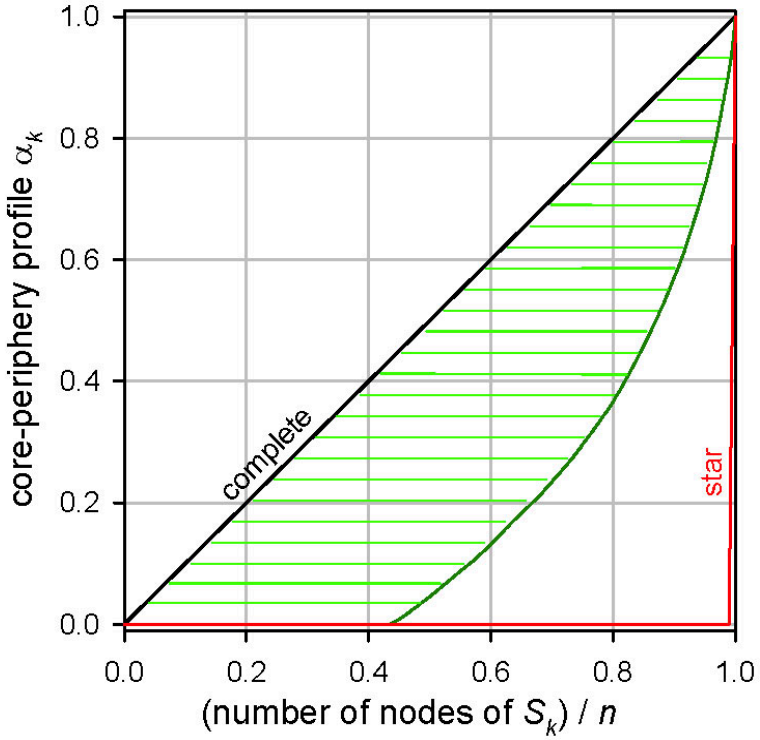


(CP) Core-Periphery index: it is based on the dynamics of a random-walker

[Della Rossa, Dercole, Piccardi, Sci Rep 2013]

A heuristic procedure for ordering the nodes from to the periphery to the core:

- start with the node i with minimal strength
- generate a sequence of sets $\{i\} = S_1 \subset S_2 \subset \cdots \subset S_N = \{1,2,\ldots,N\}$ by adding, at each step, the node attaining the minimal persistence probability $\alpha_1, \alpha_2, \ldots, \alpha_N$ (=prob. that a random walker remains in S_k at the next step).



The sequence $0 = \alpha_1 \leq \alpha_2 \leq \cdots \leq \alpha_N = 1$ is the Core-Periphery profile.

The CP index is the ([0,1]-normalized) green area between the Core-Periphery profile and the profile of the complete network.

(VI) Vulnerability index: how rapidly the aggregated weight is lost by node removal

[Dall'Asta, Barrat, Barthelemy, Vespignani, J Stat Mech Theory Exp 2006]

- Re-order nodes (=countries) by decreasing out-strength (=export) $s_i = \sum_j w_{ij}$:

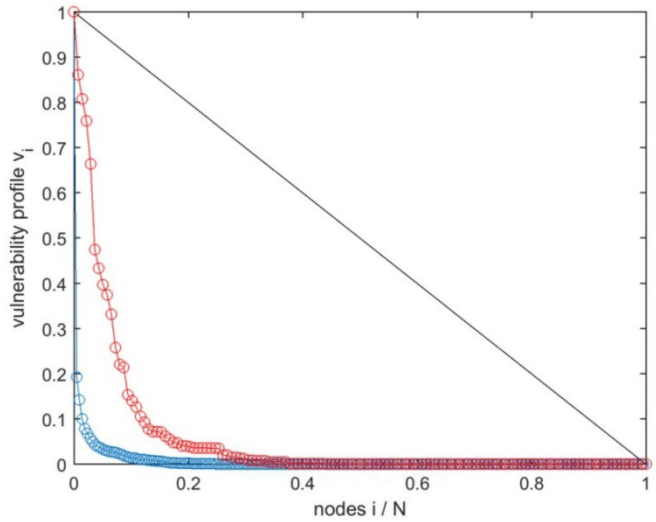
$$s_1 \geq s_2 \geq \cdots \geq s_n$$

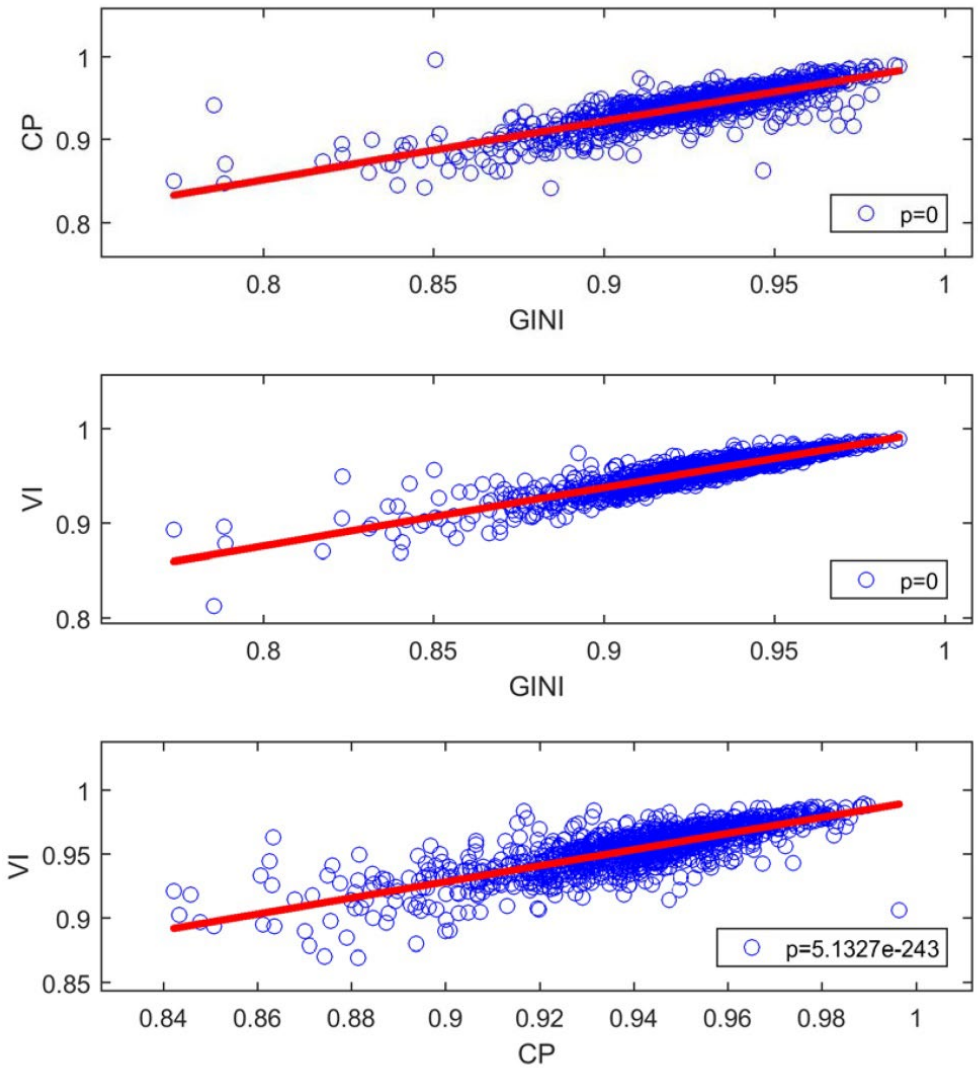
- Define the vulnerability profile as

$$1 = v_0 \geq v_1 \geq \cdots \geq v_n = 0$$

where v_k is the total network weight after (the most important) nodes $\{1,2,\cdots,k\}$ have been removed.

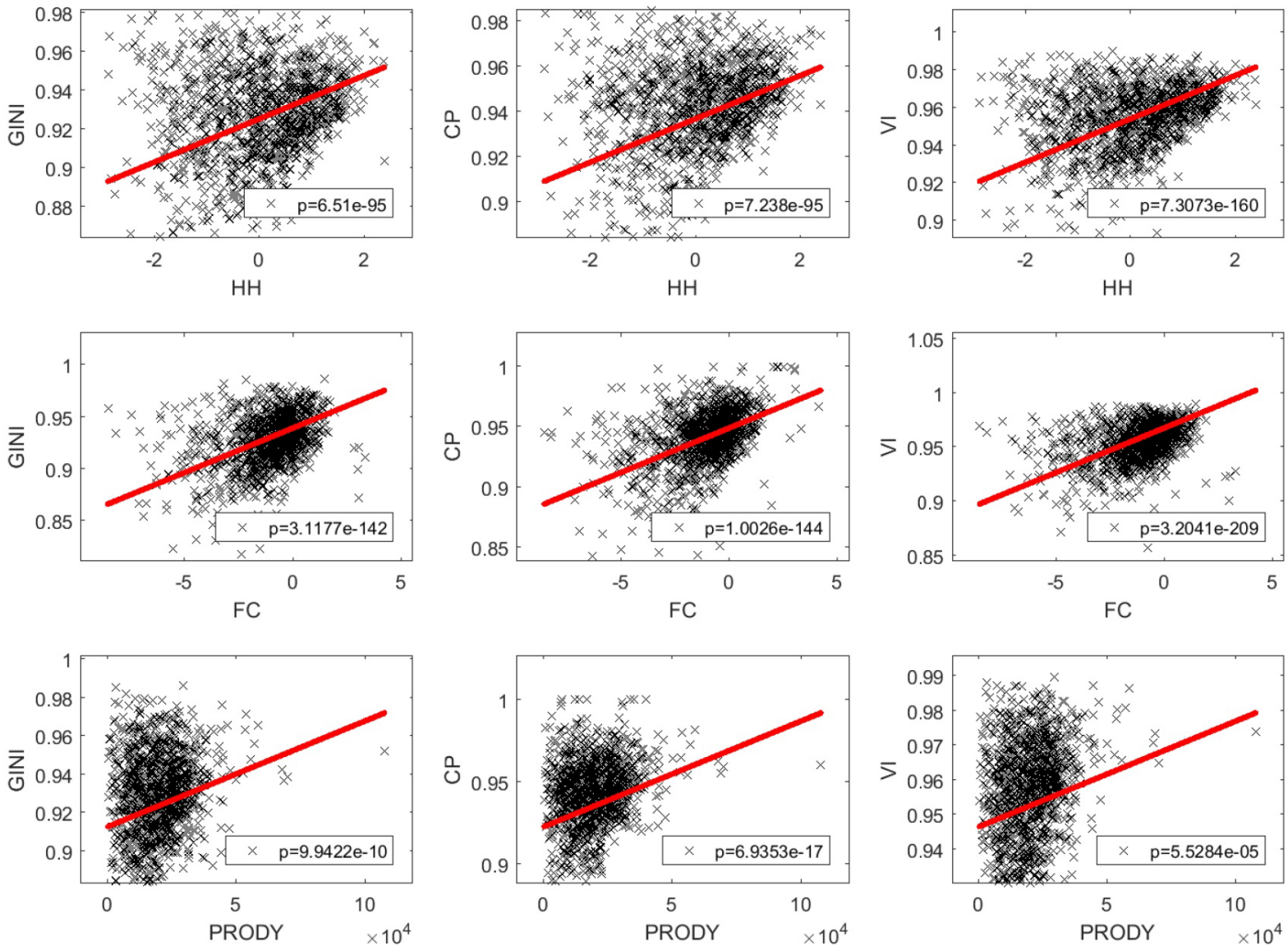
<u>Remark</u>: the VI index explicitly quantifies network robustness.





GINI, CP, and VI are also highly correlated.

RESULTS: COMPLEXITY VS CENTRALIZATION



Linear regressions
(weighted by product total export)

Complexity and centralization are positively correlated
(consistently true and statistically significant for all the 3 × 3 complexity /centralization pairs.)

Which categories (Sections) of products are the main drivers of the overall complexity/ centralization pattern?

We repeat the analysis on individual Sections:

- The Sections most responsible for the overall pattern are Machinery/Electrical, Chemicals, and Metals.

- Other Sections display similar behavior (e.g., Animal & Animal Products) but a rather small trade share.

- No Section evidences a clear opposite trend.

To conclude:

- The results confirm the conjecture on the positive correlation between complexity of products and centralization of their trade networks.
- Centralization implies fragility: The more complex are the traded goods, the more fragile are their trade networks.
- Given the relevant role played by complex goods in world trade, the global trade network appears to be uncomfortably vulnerable.

PLOS | ONE

RESEARCH ARTICLE

Complexity, centralization, and fragility in economic networks

Carlo Piccardi[1]*, **Lucia Tajoli**[2]

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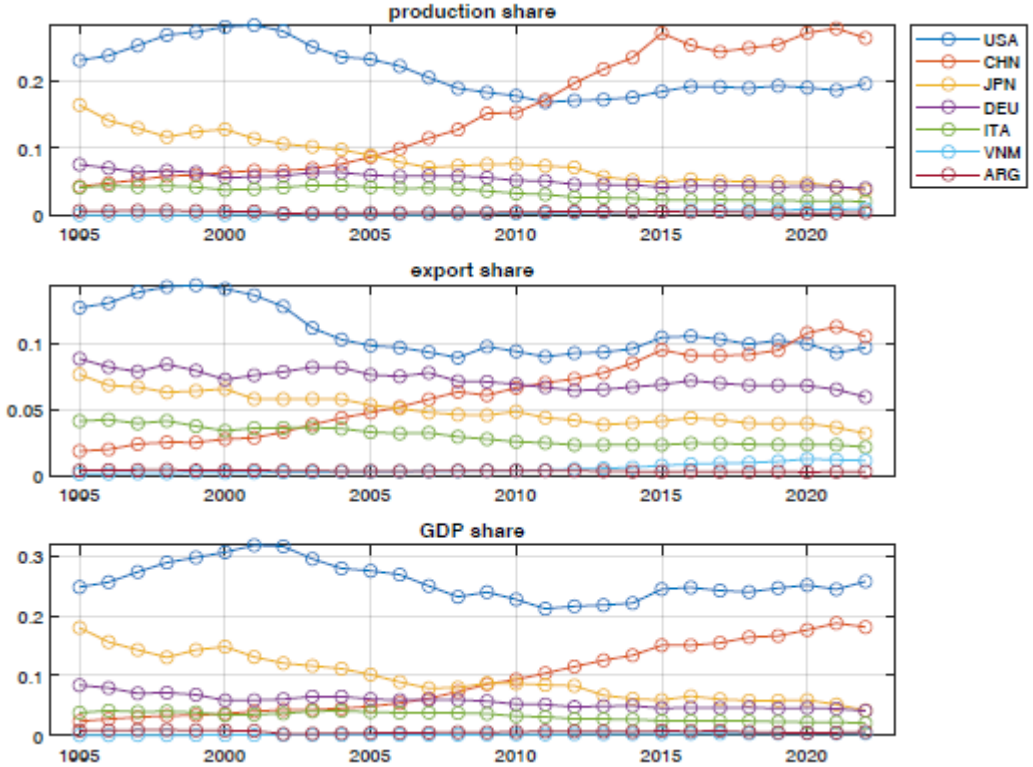
3. Role analysis: the rise and fall of nations

[C. Piccardi and L. Tajoli, The rise and fall of nations: Evolving roles in the international trade networks, J Complex Networks, in press 2026]

Interpreting the global economy solely through standard indicators (trade volumes, GDP, etc.) can obscure the structural changes taking place.

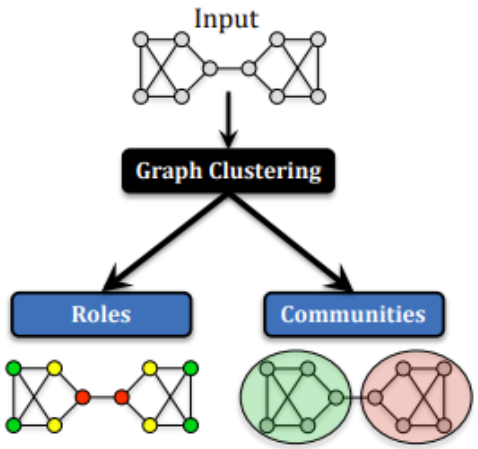


Network analysis can address the complex web of interdependent relationships between countries.

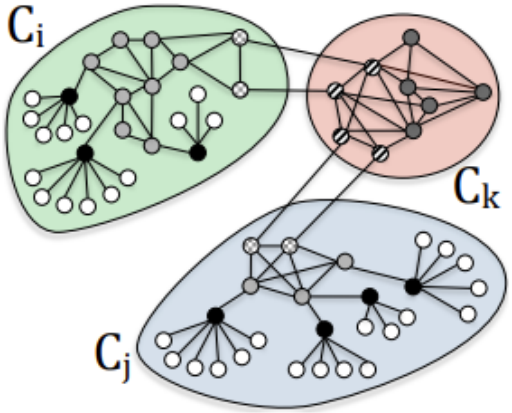
Role analysis (or role classification):

partitioning nodes into homogeneous sets based on the function they perform

In "simple" (undirected, unweighted) networks, roles are related to topological positioning (hubs, leaves, bridges, etc)



from Rossi et al, ACM Trans Knowl Discov Data 2020



from Rossi and Ahmed, IEEE Trans Knowl Data Eng 2015

Plenty of methods for roles classification:

- Feature based (+ clustering or matrix factorization)
- Random walk based ("representation learning")
- Deep learning based

Our 3-stage feature-based pipeline:

1. Feature collection (14 centralities)

In-strength, Out-strength, Total strength, Clustering coefficient, In-closeness, Out-closeness, Betweenness, In-eigencentrality, Out-eigencentrality, Autorithy-score, Hub-score, In-pagerank, Out-pagerank, Coreness

2. PCA reduction

2 components

3. Fuzzy C-means clustering

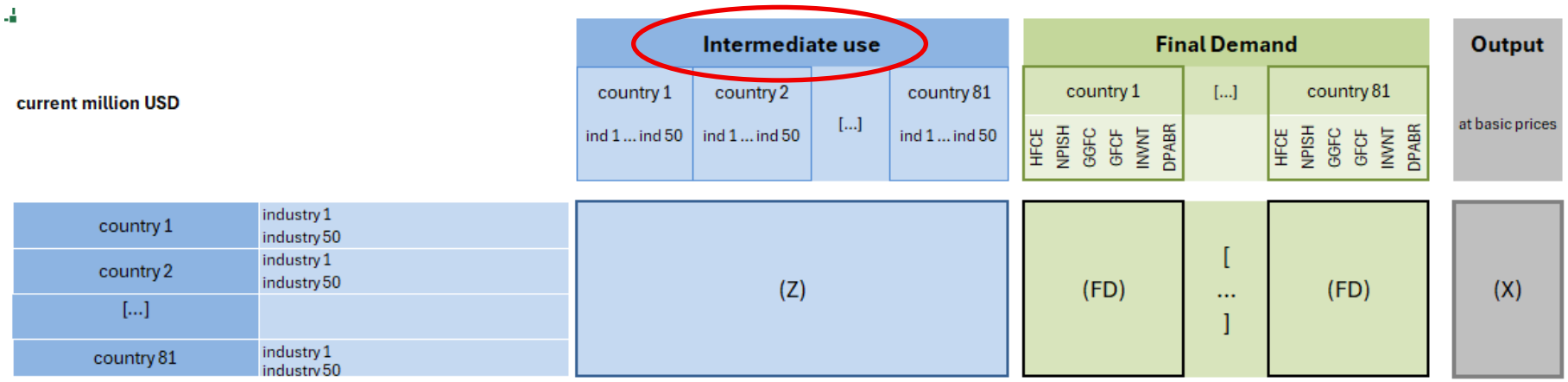
3 roles (High, Medium, Low) with membership values for each node

By repeating the above procedure for each year, we track the evolution in time of the role of each country.

Data source: OECD Inter-Country Input-Output tables

- 1995-2022 (28 years)
- 80 countries (+ Rest-of-World)
- 50 industries (goods and services)

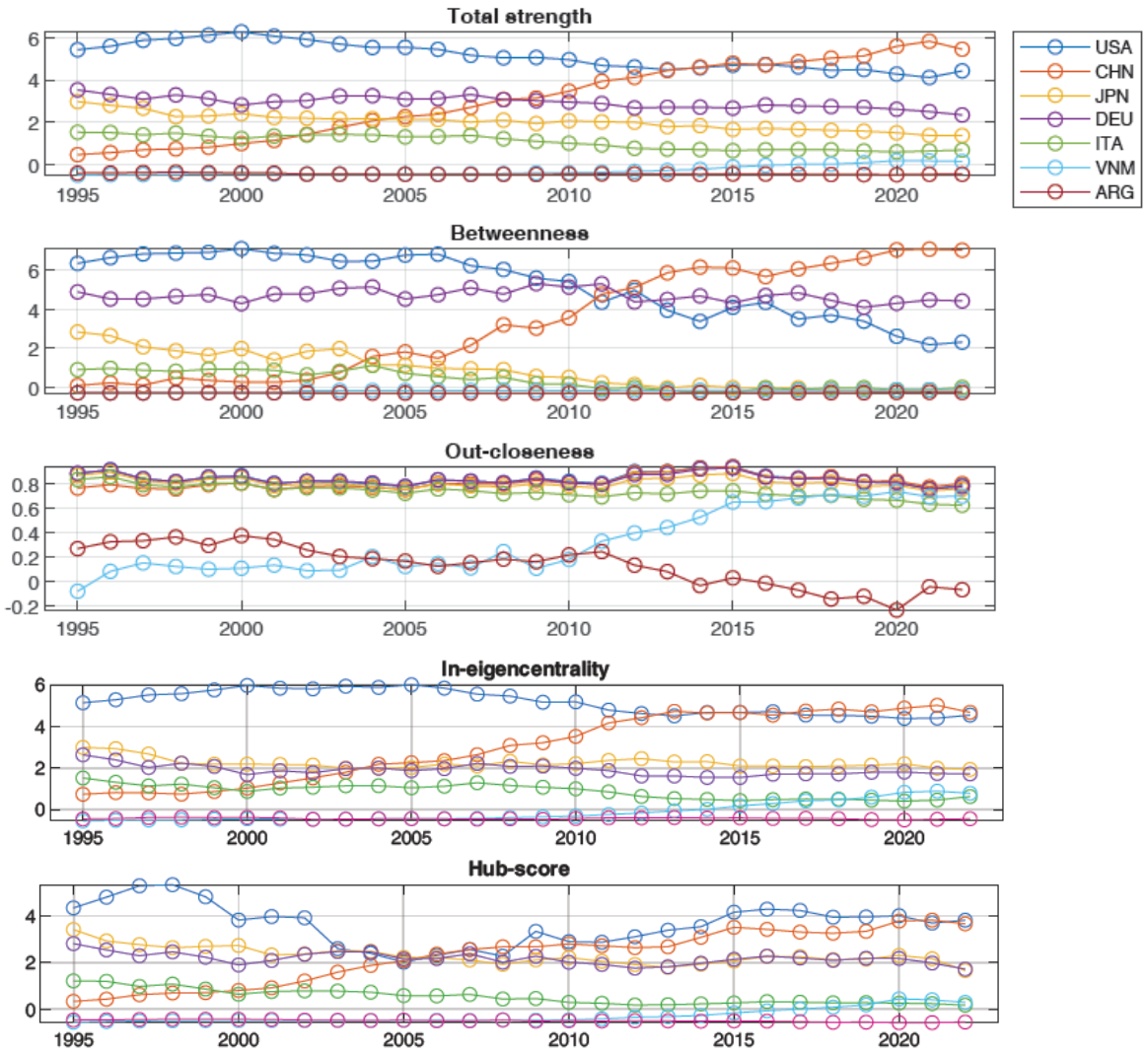
"Intermediate use" only (= transactions between industries, no final demand, no export of final goods/services): focus on Global Value Chains.



from http://oe.cd/icio

Aggregated network: $N = 81$ nodes (countries), all industries are aggregated: $w_{ij} \geq 0$ is the total value of exports from country i to country j.

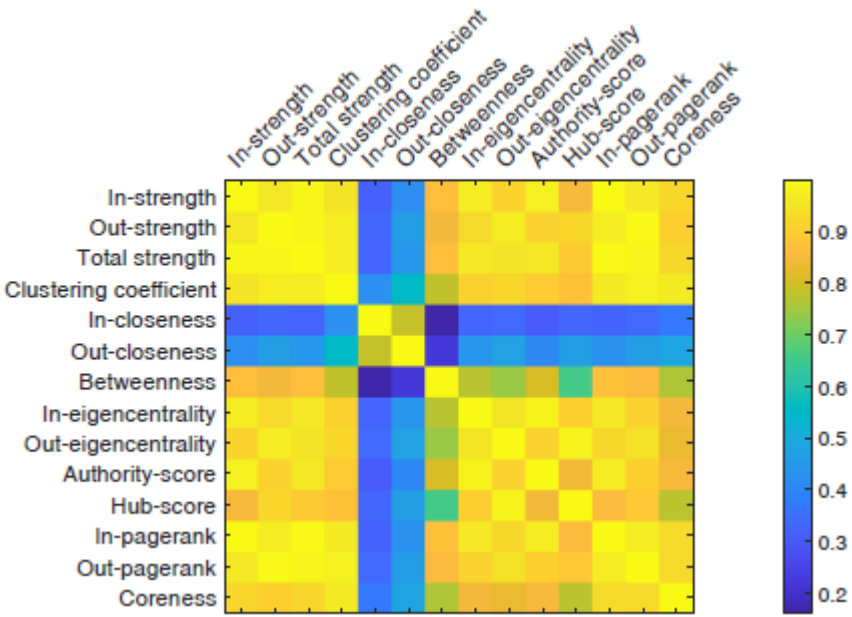
1. Feature collection



14 (standardized) centralities

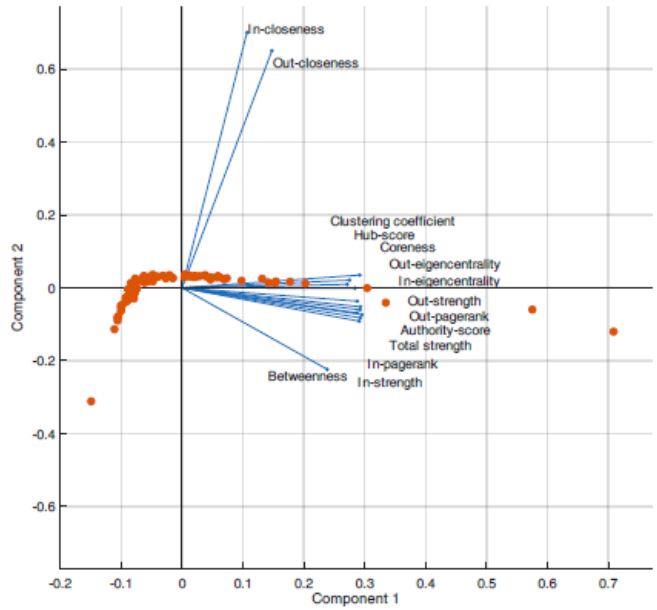
- *In-strength*
- *Out-strength*
- *Total strength*
- *Clustering coefficient*
- *In-closeness*
- *Out-closeness*
- *Betweenness*
- *In-eigencentrality*
- *Out-eigencentrality*
- *Autorithy-score*
- *Hub-score*
- *In-pagerank*
- *Out-pagerank*
- *Coreness*

2. PCA reduction



Most of the features are highly (Pearson) correlated.

PCA is used to extract the first 2 principal components (with at least 90% of aggregate variance in all years).

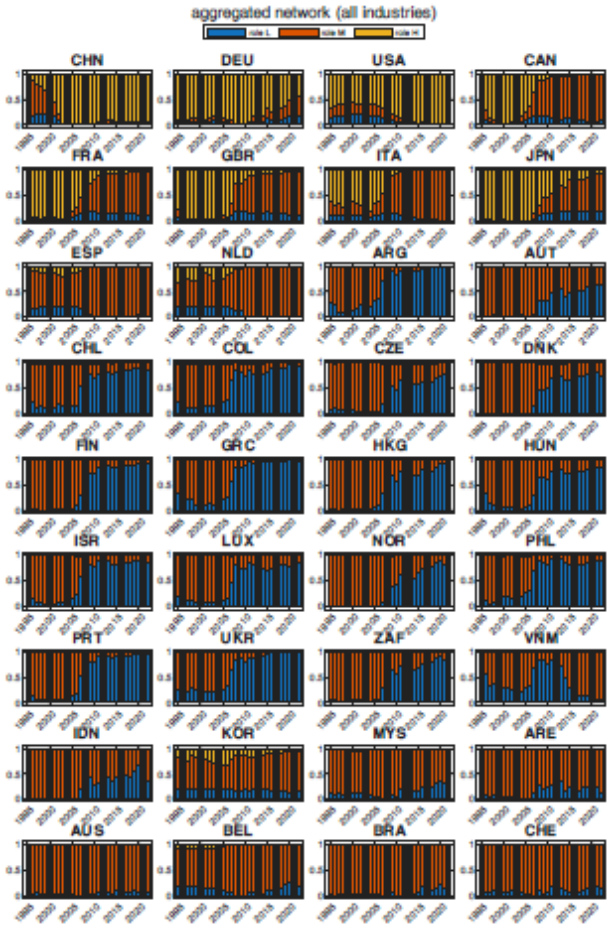


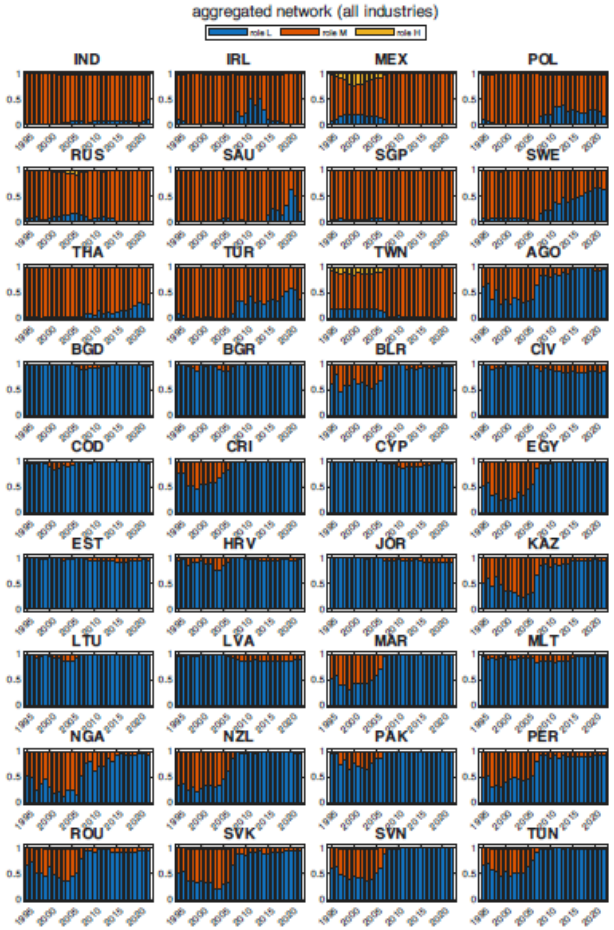
3. Fuzzy C-means clustering

Countries are classified in roles (High, Medium, Low) based on their (PCA-reduced) features.

Fuzzy membership:

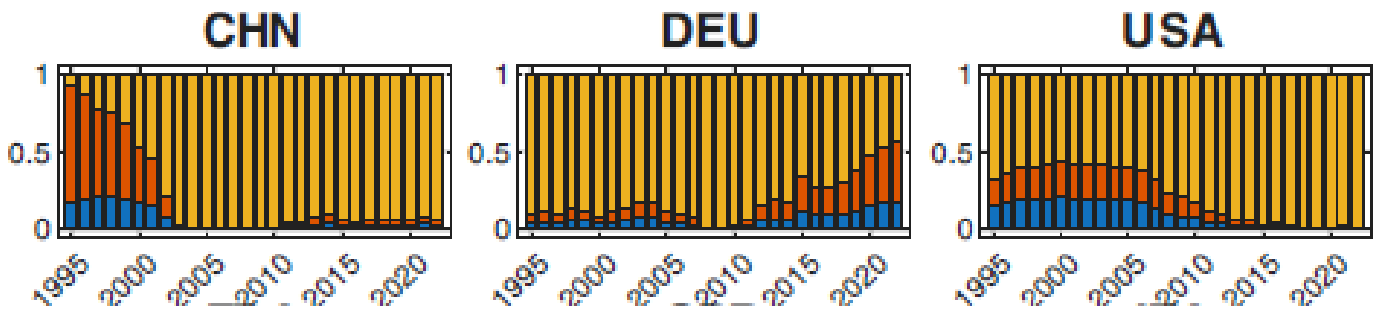
all countries i belong to all roles r with a membership value u_{ir} ($\sum_r u_{ir} = 1$)



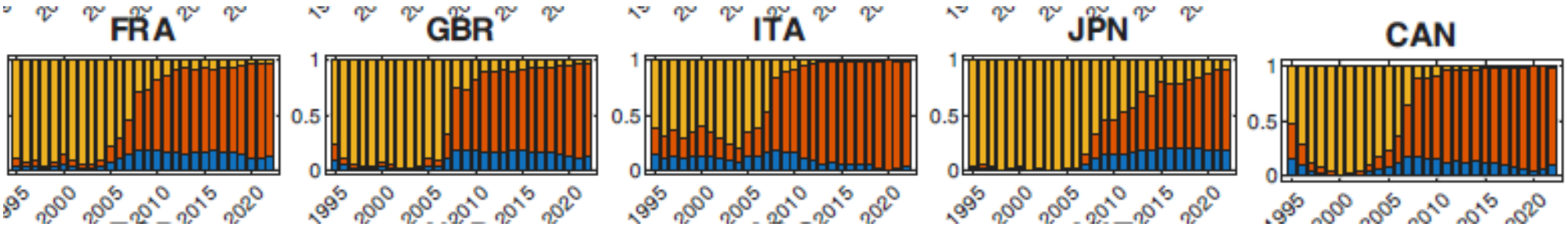


Main results:

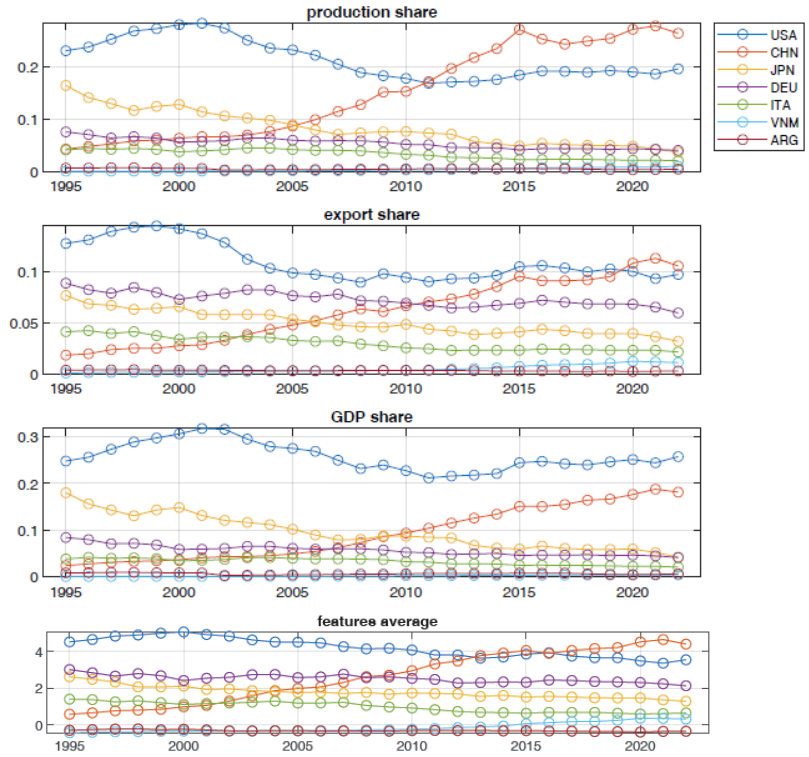
- Only CHN, DEU, USA have predominant *role H* throughout the entire time period (note the rapid rise of CHN around 2000).

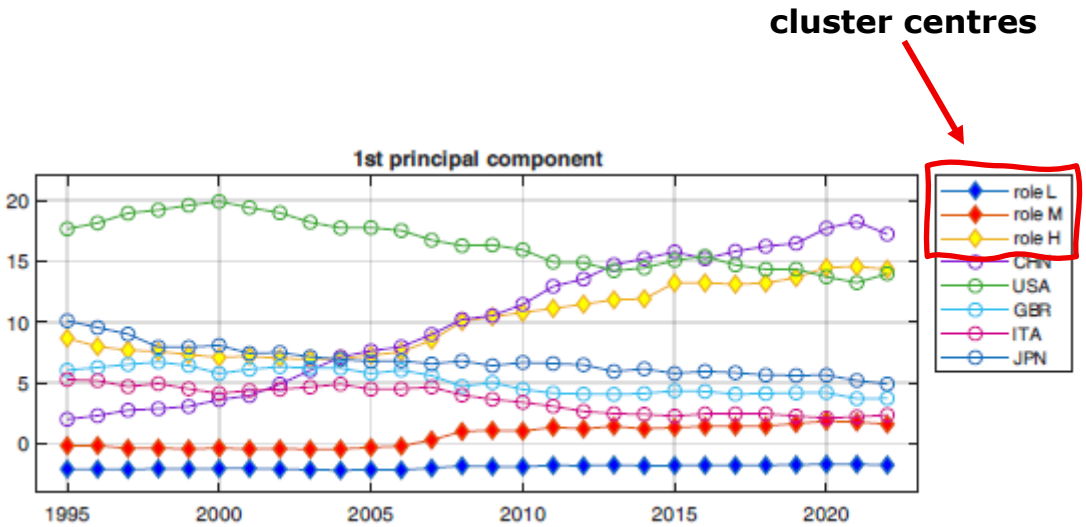


- GBR, ITA, FRA, CAN, JPN collapse in their first-level (*role H*) status and decline toward second-tier (*role M*) economies…



… despite the lack of visible collapse in economic indicators or (average) features:

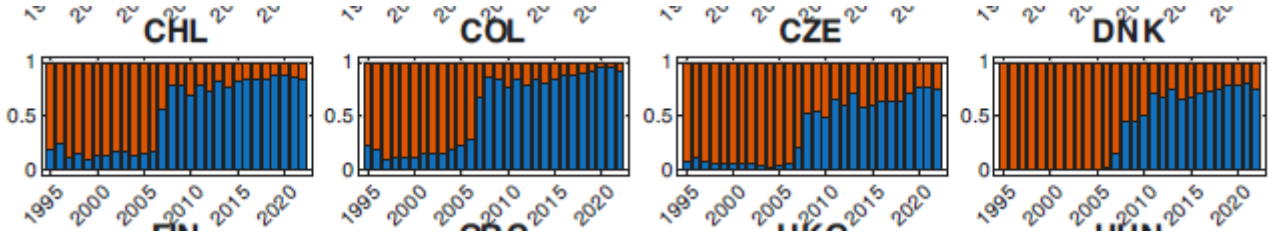




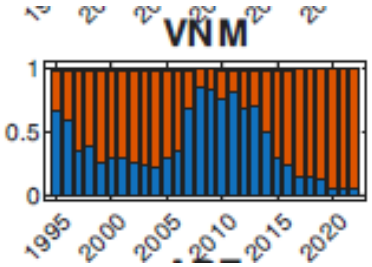
CHN and USA increased their performance disproportionately, to form a cluster by their own.

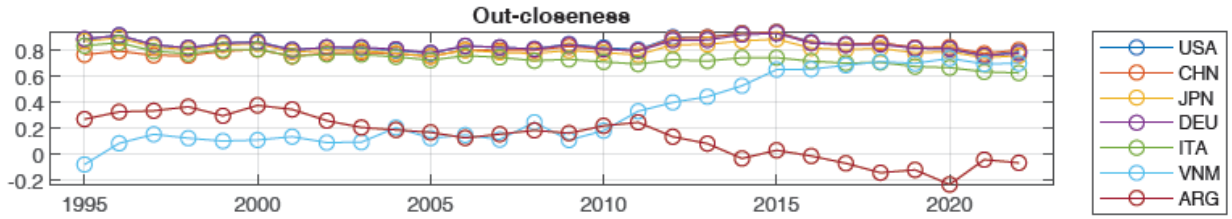
Decline of *role H* = loss of *relative* centrality

- Similarly, many countries decline from *role M* to *role L*, e.g.

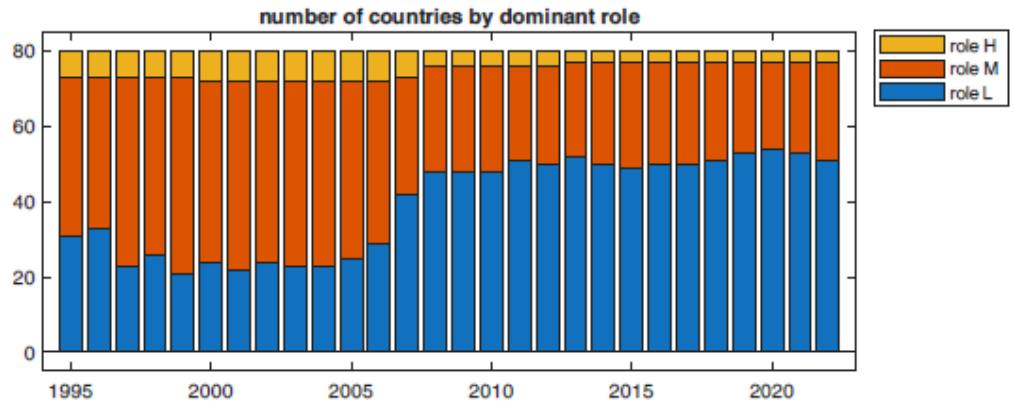


- Remarkable is the case of VNM, which jumps from *role L* to *role M* when it becomes an important GVCs supplier (see out-closeness):



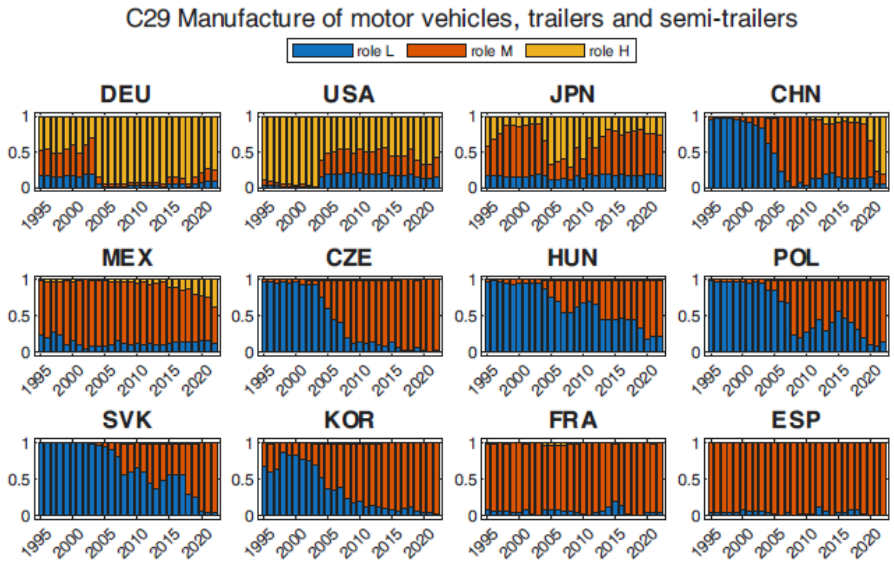


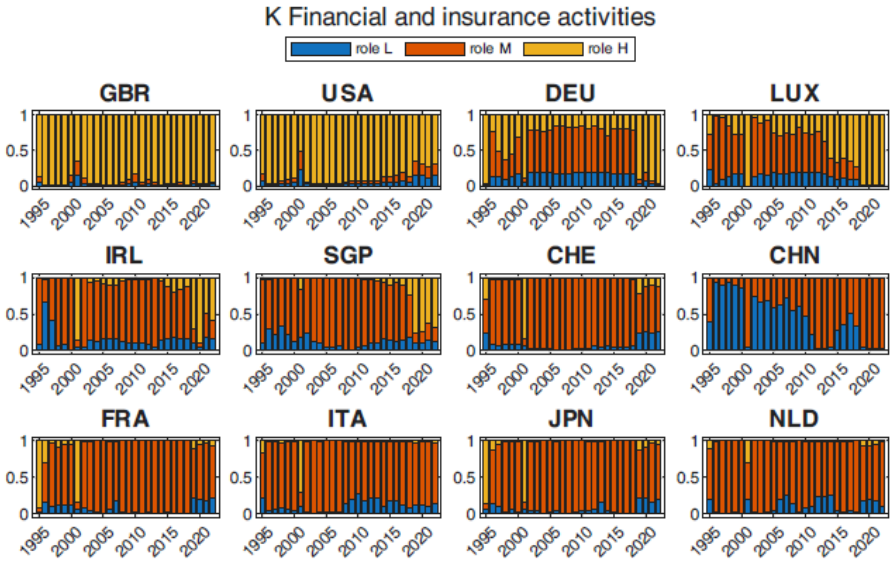
- Counting countries by dominant role reveals a progressive polarization around a few leaders (*role H*, from 7-8 to 3) and fewer intermediate countries (role M).



The same type of analysis can be performed at the disaggregated level (*industry networks*).

Two examples:





To conclude:

- A country's position within the network matters just as much as the economic indicators: countries with similar levels of trade can occupy different roles.
- Performance is relative: a country's position can deteriorate even without an absolute decline, if its competitors improve more rapidly.
- The global trading system is increasingly polarised around US and China.
- UK, France, Italy and Japan have lost their systemic status as leading nations, slipping into intermediate roles. Other countries (e.g. Vietnam) are rapidly gaining status.

Open questions:

- Is a country's role (rather than, or in addition to, economic indicators) the best indicator to assess its exposure to shocks, the effect of policies and its tariff leverage?
- Does a shift towards a bipolar system imply a rise in tensions and the proliferation of conflicts?

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Article
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The rise and fall of nations: evolving roles in the international trade networks

Carlo Piccardi[1,*] and Lucia Tajoli[2]