THE WORLD TRADE WEB: STRUCTURE, EVOLUTION AND MODELING

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Summary

The World Trade Web (WTW) is the complex network representation of the international trade system that allows an analysis at the large scale from an interdisciplinary approach. Countries are represented as nodes and commercial relations between them as links. The network representation offers a new level of description that goes beyond the country-specific analyses used in more traditional economic studies of trade. In particular, it makes possible the analysis of the indirect trade interactions among world countries. In this line of research, several tools and methodologies that have been recently developed for the analysis of any type of networks can be exploited to extract information from the WTW, and to discriminate which properties signal a nontrivial structural organization and which are likely to be originated by chance or structural constraints. Although these results have been obtained recently, and during a relatively short period of time, they have already established various robust empirical signatures of the international trade network. In some cases, these "stylized facts" turn out to be stable in time, while in others they highlight previously unrecognized changes in the system. We present a self-contained description of these advances. After a general introduction to the international trade system, we describe the possible representations of the WTW that have appeared in the literature, from its purely topological properties to its weighted structure and directionality, and the added levels of understanding they convey. We then describe various models that have been proposed to reproduce the empirical properties of the WTW, from more traditional "gravity models" which predict expected trade volumes but cannot reproduce the topology of the web, to recent network-inspired models that succeed in explaining the observed complexity of the network at a topological level. We finally discuss some open questions for future research on the world trade system as a complex network.

1. Introduction

Human societies are complex systems of individuals organized in different characteristic infrastructures. All of those, from cultural or political to scientific or economic, are interrelated forming a conglomerate that takes collective behavior beyond a mere superposition of individual activities. However, we are just starting to understand the need to develop techniques and methodologies that would allow us the necessary understanding of societies as a whole. For the moment, reductionist approaches which isolate specific social structures or patterns of interaction -complex enough on their own- dominate and have produced the valuable results we have at hand today.

In this compartmentalized panorama, one of the fundamental infrastructures of social organization is economy. It includes all systems of production, exchange and consumption of goods and services within local regions, or between countries in the world or other supranational areas. Many factors, including history, level of technological development and wealth, geographical location or political treaties impact modern economies, which specific elements are commonly aggregated in two separate blocks: the real economy, that concerns labor, production or trade, and finance, that includes debt and investment. There is a vast literature covering both fields, from the seminal works of Adam Smith in the eighteenth century to the ideas in the twentieth century of John M. Keynes and the post-Keynesians.

Zooming in on the basic mechanisms of the real economy, a fundamental form of economic interaction is trade that in most countries represents a significant share of their gross domestic product (GDP). At the international level, countries exchange goods and services usually through the structure of a market. Economies import or buy assets from other countries and at the same time export or sell to them. These transfers require a transmission infrastructure and have grown parallel to the development of communication between human groups from prehistoric times. Both have evolved boosted by waves of globalization, periods when a complex series of closely intertwined changes have dramatically increased the interactions and interdependences between an increasing number of people and human organizations in disparate geographic regions. These changes, when applied to the international economic order, refer to the presence of an intricate network of economic partnership among an increasing number of countries.

In terms of trade, two waves of globalization are identified in recent history and correspond to processes of decolonization and breaking of technical barriers inducing downturns in costs and time expenditures. The first wave is roughly identified from 1870 until the beginning of World War I and was related to lowered costs for transportation of materials and goods triggered by the Industrial Revolution, with steam power encouraging the expansion of railroad networks and oceanic routes and the telegraph connecting the two sides of the Atlantic. The second wave, from 1960 to the present -there is no complete agreement whether a third, middle wave has occurred- is intimately related to ease of exchange of information and ideas facilitated by the Information Technology Revolution, which is causing communications costs to drop dramatically at the same time that information management capabilities are exploding.

As a result of those globalization processes, the large-scale organization of the world economies exhibits nowadays a high level of local heterogeneity and of global interdependency at the same time. In this scenario, the relevance of trade goes beyond a mere exchange of goods and services. On the one hand, commercial trade flows are indeed highly correlated with other types of cross-country economic interactions -flow of services, financial assets, workers, etc.- and so stand as a good indicator for more general economic relations. On the other, and leaving aside technological, cultural and other non-economic social aspects that interplay with trade, feedback mechanisms operate between international trade and other economic variables such as production, investment, debt, or currency prices. Trade plays a central role as one of the most important interaction channels between states. It can act, for instance, as a substrate for the transmission of economic policies, cycles, and shocks like the 1997 Asiatic crisis, which shows how economic perturbations originated in a single country can somehow propagate globally in the world. This is in line with the idea of the world becoming a global village. In a broad sense, this implies that the collapse of the barriers in human communication allows that incidences in one part of the system affect all the rest.

Therefore, it seems natural to analyze the international trade system from a global perspective taking into account every country and its trade relationships regardless of its size or wealth. This is in contrast to traditional analyses of international commerce that have been based on local approaches. These have focused, with a few exceptions, on bilateral trade exchanges, commercial relations between pairs of countries. However, the large size and the entangled connectivity pattern characterizing the international trade organization points out to a complex system, whose properties depend on its global structure. Although economic or political institutions can have an impact in local regions, at the large scale the world trade web resembles other complex self-organized systems, which evolve without the intervention of any centralized control that regulates its growth or performance. At this scale, an integrative interdisciplinary framework coming from complex networks science considers the set of all exchanges in the system as a whole and has proven to be successful in uncovering the relation between local and global emerging features and in providing insight into some of the global properties and evolution of the international trade system.

Within the complex network representation, countries correspond to nodes and trade relationships among them to links. As a tool of visualization, graphs of bilateral trade relations have been used in recent years to help analyze gravity models, often proposed to account for the world trade patterns and their evolution. However, the importance of the complex network approach goes beyond the auxiliary character of visual representations and introduces new interdisciplinary methodologies for the analysis of the world trade web at the large scale. As specific examples, the effects of one economy on another can be assessed more reliably based on the complete set of complex interactions that interwove the whole system, and correlations between the income of countries measured by their Gross Domestic Product (GDP) and their role as net producers or net consumers can be explored. From a more general perspective, the complex network approach suggests that the evolution of the WTW is guided by collective phenomena, and that self-organization plays a crucial role in structuring its heterogeneities and its hierarchical architecture.

The next sections present a review of the world trade web as a complex network. Various representations of the network are possible. The simplest approach is to consider it as undirected, which amounts to ignore the directionality of trade. This representation can either discard the volume of trade, in which case one has an unweighted undirected network, or take trade volume into account, so that a weighted undirected network is obtained. Such undirected approaches already reveal a non-trivial and heterogeneous organization, which is discussed in Section 2. More refined descriptions focus on the direction of trade. In the unweighted case, this highlights peculiar patterns in the reciprocity of trade relationships. In the weighted case, the directionality of exchanges reveals a strong heterogeneity in the magnitude of the different bilateral trade relations and their asymmetry. Directed approaches are reviewed in Section 3. In Section 4 we present a series of attempts that have been made to model the observed properties of the network. These are essential issues in the understanding of the interplay between the underlying structure and the principles that rule the functional organization and evolution of the world trade web. Finally, we list some open questions for future research on the international trade network in Section 5 and make our concluding remarks in Section 6.

2. The Undirected Network Approach

Complex networks are ubiquitous in nature and among manmade systems. Examples range from intra-cell networks –gene regulatory, metabolic, protein interaction, signal transduction networks…- or inter-cell networks –nervous systems and brains, tissues- where cell functionality is sustained by the network structure, to technological webs –the Internet, the world wide web, wireless communication networks…- where topology determines the system's ability to transmit information, or to social networks of interacting individuals. Over the last years, complex networks have been the subject of an intense research activity both on empirical and theoretical grounds that have set the grounds for complex network science.

Complex networks are structures of a large number of elements linked by nonlinear interactions that self-organize and give place to emerging phenomena. Real networks are not regular lattices neither completely random. Their structure lies in between and most of them share a set of universal topological features despite belonging to very different domains. Typically, networks show the following properties: scale-free (SF) degree distribution $P(k) \sim k^{-\gamma}$ with $2 < \gamma \leq 3$, where the degree k is defined as the number of nearest neighbors of a node; the small-world property, which states that the average path length between any pair of vertices counted as the number of intermediate neighbors grows at most logarithmically with the system size; and a high clustering coefficient, that is, the neighbors of a given vertex are interconnected with high probability; in addition, degree-degree correlations that account for the probability that a vertex of degree k is connected to a vertex of degree k' and is said assortative if highly connected vertices tend to attach to other highly connected vertices (characteristic of social networks, such as scientific collaboration networks), and disassortative if conversely highly connected vertices tend to attach to poorly connected ones (technological networks such as the Internet).

As we describe below, the empirical characterization of the international trade system as a graph built upon the trade relationships between different countries in the world displays the typical properties of most complex networks. It has a broad degree distribution, where most countries have a low number of connections while just a few trade with nearly all the system; it is a small-world, so that each pair of countries is very close in topological distance; it displays a decreasing degree-dependent clustering coefficient, signaling that countries trading with a well connected one are poorly interconnected among them, and it presents degree-degree correlations between different vertices, with high-degree countries connecting preferentially to low-degree ones. All these properties make the world trade web a complex network, which is far from being well described through a classical description.

2.1. Topological Features

The WTW is customarily constructed from databases (see Section I in Appendix) detailing the import and export exchanges of merchandizes between pairs of countries in the world. Imports correspond to goods brought into one country typically from being bought to another country, and provide domestic consumers with foreign production. In its turn, exports correspond to goods from one country brought into another country typically from being sold, and provide foreign consumers with domestic production. Therefore, exports render an inflow of money into the country while imports generate an outflow. Notice that the same commercial exchange between two countries would be at the same time an importation for one of them while an export for the other, and that one country can simultaneously have import and export exchanges with another.

2.1.1. Number of Countries in the World Trade System

The number of countries in the world trade system has been increasing during the last century (see Figure 1). The progressive crumbling of the Imperial Colonies during the sixties and seventies, and the former Soviet Union could basically explain this fact. However, as shown in the inset, the density of connections has remained constant, which indicates that the average number of trade partners has grown, during the same period, linearly with the number of countries. This can be understood by assuming that, when a country splits, the different offsprings usually maintain a fraction of the trade relationships of the former unit. This mechanism implies that the evolution of the number of connections evolves according to the equation

$$\frac{dE}{dN} = \alpha \langle k(N) \rangle, \qquad (1)$$

where E is the total number of trade relationships in the system when its size in number of countries is N and $\langle k(N) \rangle$ is the average number of trade partners of a country at the same moment in time. Since, by definition, $\langle k(N) \rangle = 2E / N$, we obtain that $E \sim N^2$ and, thus $\langle k(N) \rangle \sim N$, in accordance to the empirical observations.

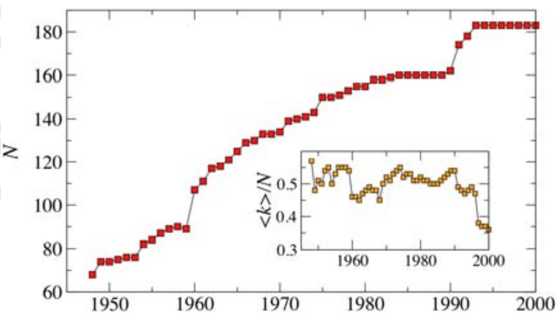

Figure 1. Evolution of the number of countries in the world during the second half of the XXth century. Inset: density of connections during the same period. (DBII in Section I of Appendix).

2.1.2. Network Reconstruction

The empirical data allow graph reconstructions of the international trade system with different levels of detail and information content. In general, countries are represented as nodes and edges join pairs of nodes based on some metric related to trade. The most basic representation is a graph where a pair is connected through an undirected and unweighted link whenever a commercial exchange between them is reported. More sophisticated representations take also into consideration the amount of the exchange, so that links are not anymore binary, just present or absent, but have an associated weight that introduces a new level of heterogeneity in the picture.

On top of this, the directionality of the connections can also be taken into account to consider links with different orientation and/or different incoming and outgoing weights, or purely directional weighted connections corresponding to net trade imbalances.

Despite its simplicity, the most basic representation of the WTW as an undirected unweighted graph already provides relevant information about the international trade system. The adjacency matrix $\mathbf{A}$ that compiles the connectivity information between nodes in the network has entries a_{ij} with values 1 or 0, depending respectively on whether country i has or not an exchange with country j. The dual attribute of trade exchanges, that at the same time are imports for one country while exports for the other, can be exploited to reconstruct a consistent unweighted undirected adjacency matrix $\mathbf{A}$ from the import and export databases. In mathematical terms $I_{ij} = E_{ji}$, where $\mathbf{I}$ is the import adjacency matrix with entry I_{ij} equal to 1 if i imports from j and 0 otherwise, and $\mathbf{E}$ the export adjacency matrix with E_{ij} equal to 1 if country i exports to country j. The adjacency matrix $\mathbf{A}$ is calculated as

$$a_{ij} = \frac{I_{ij} + E_{ji}}{1 + \delta_{I_{ij}+E_{ji},2}}, \qquad (2)$$

where $\delta_{x,y}$ is the Kronecker delta function. This method enables to obtain an adjacency matrix where each connection is relevant at least to one of the two involved countries, even when only partial information is reported, as in the case of a bounded number of merchandizes. An alternative reconstruction of the undirected adjacency matrix would consider just bidirectional edges, but in the following we consider $\mathbf{A}$ as defined in Eq. (2).

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Maria I. Loffredo is assistant professor in Mathematical Physics at the University of Siena. After receiving her degree in physics in Salerno, she spent some time at Princeton University. Her research interests are in the fields of stochastic quantization, mathematical modelling of financial markets and econophysics. She is currently involved in the application of network theory to economics and finance.