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Worldwide spreading of economic crisis

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Abstract. We model the spreading of a crisis by constructing a global economic network and applying the susceptible–infected–recovered (SIR) epidemic model with a variable probability of infection. The probability of infection depends on the strength of economic relations between a given pair of countries and the strength of the target country. It is expected that a crisis that originates in a large country, such as the USA, has the potential to spread globally, such as the recent crisis. Surprisingly, we also show that countries with a much lower GDP, such as Belgium, are able to initiate a global crisis. Using the k-shell decomposition method to quantify the spreading power (of a node), we obtain a measure of 'centrality' as a spreader of each country in the economic network. We thus rank the different countries according to the shell they belong to, and find the 12 most central ones. These countries are the most likely to spread a crisis globally. Of these 12, only six are large economies, while the other six are medium/small ones, a result that could not have been otherwise anticipated. Furthermore, we use our model to predict the crisis spreading potential of countries belonging to different shells according to the crisis magnitude.

S Online supplementary data available from stacks.iop.org/NJP/12/113043/mmedia

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Contents

1. Introduction

A global economic crisis, such as the recent 2008–2009 crisis, is certainly due to a large number of factors. In today's global economy, with strong economic relations between countries, it is important to investigate how a crisis propagates from the country of origin to other countries in the world. Indeed, several significant crises in recent decades have originated in a single country. However, it is still not clear how and to what extent domestic economies of other countries may be affected by this spreading, due to the inter-dependence of economies [1]. Here, we use a statistical physics approach to deal with the modern economy, as has been done successfully in recent years for the case of financial markets and currencies [2]–[10]. More precisely, we view the global economy by means of a complex network [11]–[14], where the nodes of the network correspond to countries and the links to their economic relations.

To generate the economic network, we use two databases in order to avoid any bias due to the network selection. A global Corporate Ownership Network (CON) is extracted from a database of the 4000 world corporations with the highest turnover, obtained from the Bureau van Dijk[6]. This database includes all of the corporate ownership relations to their 616 000 direct or indirect subsidiaries for the year 2007. The trade conducted by these companies, in terms of import/export, is a large fraction of the total world trade. Furthermore, the network of subsidiaries is a direct measure of the investment of large corporations in order to grow. Foreign investment is a key factor in the development of global and local economies while, as recent economic crises suggest, the role of large corporations in the spreading of crisis in the global economy is not yet clearly understood. The second network, the International Trade Network (ITN), is extracted by the 2007 version of the CHELEM database obtained from the Bureau van Dijk (see footnote 6), which contains detailed information about international trade, and GDP values for 82 countries in millions of US dollars. This database provides us with an economic network based on import/export relations between countries.

For both networks, we are able to locate a nucleus of countries that are the most likely to start a global crisis, and to sort the remaining countries' crisis spreading potential according to their 'centrality'. Initially, a crisis is triggered in a country and propagates from this country to others. The propagation probability depends on the strength of the economic ties between the countries involved and on the strength of the economy of the target country. Our results show that, besides the large economies, even smaller countries have the potential to start a significant crisis outbreak.

[6] Bureau van Dijk Electronic Publishing (BvDEP) http://www.bvdep.com/

2. Analysis

CON is a network that connects 206 countries around the globe, using as links the ownership relations within large companies. If companies listed in country A have subsidiary corporations in country B, there is a link connecting these two countries directed from country A to country B. The weight of the link, w_{AB}, equals the number of subsidiary corporations in country B controlled by companies of country A. Next, if companies from country B have subsidiary corporations in country C, then again there is a weighted link, w_{BC}, connecting these two countries directed from B to C, and so on. In this way we obtain a network with a total of 2886 links among 206 nodes (countries). Of these links, 685 are bi-directional, meaning that there is a link from node i to j, as well as a link from node j to i, and the remaining 1516 are uni-directional.

We assume that the total link weight between a pair of nodes (countries) ij is the sum of all links independent of their direction, $w_{\mathrm{tot}}^{(ij)} = w_{ij} + w_{ji}$. The total link weight represents the strength of the economic ties between two countries in the network. We quantify the total economic strength of a country i by its total node weight, $\tilde{w}_{\mathrm{tot}}^{i} = \sum_j w_{ij} + \sum_j w_{ji}$, i.e. summing the weights of all links of node i. The probability density distributions of the total node weights and of the total link weights are skewed and heavy tailed, as shown in figure S1 in the supplementary information (available from stacks.iop.org/NJP/12/113043/mmedia). We find an almost linear relation between $\tilde{w}_{\mathrm{tot}}^{i}$ and the GDP of country i (as shown in supplementary figure S2 (available from stacks.iop.org/NJP/12/113043/mmedia)), which indicates that the total weight of a country in our network is strongly correlated to a traditional economic measure.

ITN is calculated from the second database after we aggregate the trade activities between all pairs of countries. Using the trading relations between each pair of countries, e.g. A and B, we can create a bi-directional network where E_{AB} represents the export of A to B, and E_{BA} represents the export of B to A. Of course, E_{AB} is equal to I_{BA}, which stands for imports of B from A. In accordance with the above notation, the total link weight is given by $w_{\mathrm{tot}}^{(ij)} = E_{ij} + E_{ji}$, but the total node weight $\tilde{w}_{\mathrm{tot}}^{i}$, which quantifies the economic strength of a node, equals its GDP value.

To identify the uneven roles of different countries in the global economic network, we use k-shell decomposition and assign a shell index, k_s, to each node. The k-shell decomposition is a method that can identify how central a node is in the network. The higher its k_s value, the more central this node is, while this centrality is very important for its spreading capabilities [15]–[17]. Nodes in the highest shell, called the nucleus of the network, represent the most central countries. To determine the k-shell structure, we start by removing all nodes having degree $k = 1$, and we repeat this procedure until we are left with only nodes having degree $k \geqslant 2$. These nodes constitute shell $k_s = 1$. In a similar way, we remove all nodes with $k = 2$ until we are left with only nodes having degree $k \geqslant 3$. These nodes constitute $k_s = 2$. We apply this procedure until all nodes of the network have been assigned to one of the k-shells. With this approach, we view the network as a layered structure. The outer layers (small k_s) include the loosely connected nodes at the boundary of the network, while in the deeper layers we are able to locate nodes that are more central. An illustration of this structure is shown in figure 1.

To identify the nucleus of CON, we consider in the k-shell the network having only links with weights above a cut-off threshold w_c. By using different threshold values, we locate different nuclei of different sizes, as shown in figure 2(a). However, for the whole range of

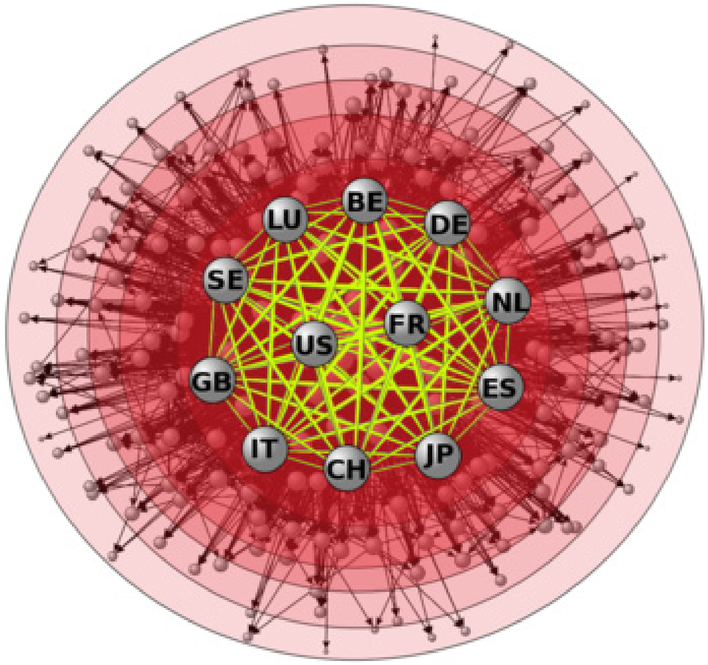

Figure 1. Illustration of the layered structure of the global economic network of 206 countries of the world using the large corporation subsidiary relations. The layers are a schematic drawing of shells obtained by the k-shell method. The outer layers include the loosely connected countries, while at the centre we highlight the nucleus of the 12 countries we identified.

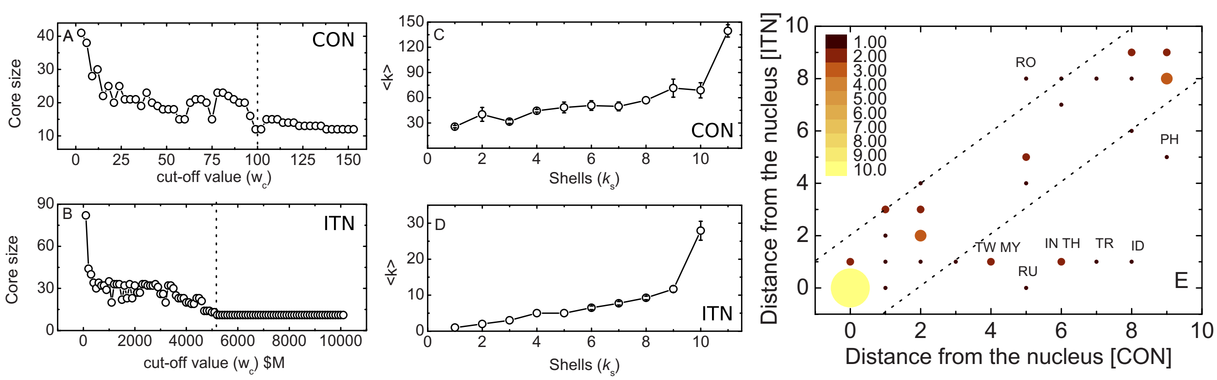

Figure 2. k-shell decomposition of the network. (a) Size of the nucleus for different cut-off values, using CON. (b) Size of the nucleus for different cut-off values, using ITN. (c) Average degree of the countries of shell k_s for CON. The higher the shell number, the closer we get to the nucleus of the network. This plot corresponds to the structure obtained for the cut-off value $w_c = 100$. (d) Average degree of the countries of shell k_s for ITN. This plot corresponds to the structure obtained for the cut-off value $w_c = 5100\$M$. (e) Scatter plot showing the distance from the nucleus of different countries for both CON and ITN.

the threshold values used, namely for $w_c \in [0, 150]$, we are able to identify 12 countries that are always present in the nucleus with $k_s = 11$. Furthermore, for $w_c \geqslant 100$, the nucleus is fully connected and always includes only the same 12 countries. These countries are the USA (US), the United Kingdom (GB), France (FR), Germany (DE), the Netherlands (NL), Japan (JP), Sweden (SE), Italy (IT), Switzerland (CH), Spain (ES), Belgium (BE) and Luxembourg (LU), sorted according to their total node weight $\tilde{w}_{tot}$.

When performing the k-shell decomposition method on the ITN, we locate a nucleus at $k_s = 10$ composed of 11 countries, which is stable and always the same for $w_c \geqslant 5100\$M$, as shown in figure 2(b). Actually, we may view it as a 12-country core, because the CHELEM database considers Belgium and Luxembourg as one trade zone, and therefore the core consists of the following 12 countries: China (CN), Russia (RU), Japan (JP), Spain (ES), the United Kingdom (GB), the Netherlands (NL), Italy (IT), Germany (DE), Belgium (BE), Luxembourg (LU), the USA (US) and France (FR). This nucleus is almost the same as the nucleus found for CON. There are only two differences, which can be clearly understood due to the complementary nature of the networks. The first difference is that Sweden (SE) and Switzerland (CH) are now located at shell 9 in the ITN, which is one shell below the core. The second difference is that China (CN) and Russia (RU) are now part of the nucleus, while in CON they were located one shell and five shells away from the core, respectively. The presence of these countries in the nucleus of the ITN, and their absence in the nucleus of CON can be explained considering the unusual structure of their economies. In CON, for example, only 7.5% of the corporations have headquarters in China, but trade with China is more than 15% of the total global trade. This happens because most of the goods exported by China are manufactured there under Western brand names. Therefore, a large fraction of China's total trade volume comes from subsidiaries of Western corporations.

Compared with the other shells, countries in the nucleus not only are strongly interconnected among themselves but also have many links to other nodes of the network. This is clearly demonstrated in figure 2(c) for CON and in figure 2(d) for ITN. More specifically, for CON, the 12 countries of the nucleus have a significantly large average degree $\langle k \rangle = 139 \pm 7$ compared to countries in the shells below, where $\langle k \rangle = 69 \pm 9$ for shell $k_s = 10$. For ITN, the average degree of the nucleus is $\langle k \rangle = 28 \pm 2$, while the average degree of shell $k_s = 9$ is $\langle k \rangle = 12 \pm 1$. Surprisingly, not all 12 countries have the largest total weights or the largest GDPs. Nevertheless, our results suggest that they do play an important role in the global economic network. For CON, we find that six of the G8 members are part of the nucleus (except for Russia and Canada, which belong to lower shells), while the other six are smaller countries in absolute size (relative to the large countries). This is explained by the fact that these smaller countries do not support only their local economy but are also a haven for foreign investments, as they attract funds from large countries for taxation purposes, safekeeping, etc, and a problem in such investments can easily lead to a chain reaction in other countries. Countries such as LU and CH, which are the headquarters for some of the world's largest companies and subsidiaries, interact very strongly with a large number of countries. For example, about 95% of all pharmaceutical products of the Swiss industry are not intended for local consumption but for exporting.

Although both CON and ITN are based on different databases, it is interesting that most of the countries are located in very close k-shells, supporting the robustness of our approach. This is shown in the scatter plot of figure 2(e), which maps the change in the k-shell ranking for both networks. The ranking is done in units of distance from the nucleus. We find that most of the countries are located at almost the same distance from the nucleus for both networks, since 82% of the countries are inside the two lines (figure 2(e)), representing distance $\leqslant 1$. The few countries that are in very different k-shells are usually large countries (in terms of population) that are very active in terms of trade but do not own many large corporations with global status, e.g. Turkey (TR) and India (IN).

It should be noted that when we apply the clique percolation method (CPM) [18], both CON for $w_c \geqslant 100$ and ITN for $w_c \geqslant 5100$\$M, we find that the strongest connected communities are the same with the nuclei found using the k-shell method, as shown in supplementary figure S3 (available from stacks.iop.org/NJP/12/113043/mmedia).

Next we study how an economic crisis can propagate in these networks. An economic crisis is a very complex phenomenon that cannot be reduced to an 'all or nothing' situation. In order to get some insight into the mechanisms of crisis spreading and the role of network topology in this spreading, we applied a susceptible–infected–recovered (SIR)-type model. The SIR model has been used successfully to model the spreading of epidemics in various networks [19, 20]. The basic characteristic of SIR is that it usually assumes a fixed probability for neighbour-to-neighbour infection. In our case, we assume a probability that depends on the economic weights of the links and the strength of the targeted country (see equation (1)). Initially all nodes are in the susceptible (S) state. We chose one node (country) and set it to be in a crisis (infected) state (I). During the first time step, it will infect all of its neighbouring nodes with probability calculated from equation (1), and the status of the infected nodes switches from S to I. This process is repeated, with all of the infected nodes trying to infect during each time step their susceptible (S) neighbours. After each time step, the status of the original infected nodes changes to recovered (R) and can no longer infect or become infected. In our economic crisis epidemics, recovery means that a set of successful measures has been applied and the country overcomes the crisis. The simulation stops when there are no more infected nodes or when all of the nodes have been infected.

We assume for both CON and ITN that the probability p_{ij} of node i infecting its neighbouring node j depends on the total weight of the link, the total weight (strength) of the targeted node and on the magnitude m of the crisis,

$$p_{ij} \propto m \cdot w_{\text{tot}}^{(ij)} / \tilde{w}_{\text{tot}}^{j}. \tag{1}$$

The ratio $w_{\text{tot}}^{(ij)} / \tilde{w}_{\text{tot}}^{j}$ represents the relative economic dependence of country j on country i, which we consider as a factor in the probability that country j will be infected by country i. The factor m represents the strength of the crisis and can generally have any positive value. However, an arbitrarily large value of m could result in $p_{ij} \geqslant 1$, which would mean that the process is not stochastic anymore and the crisis will spread in a single step.

In economic relations, directionality plays an important role. For CON, a crisis in a subsidiary could create some problems in the mother company, but if there is a crisis in the mother company, its effect on the subsidiaries is always significantly more severe. To account for directionality, we study the case when we keep only one link, directed or undirected, for each pair of connected nodes. To this end, we calculate for all pairs of nodes the quantity

$$T = \left| \frac{w_{ij} - w_{ji}}{w_{ij} + w_{ji}} \right|. \tag{2}$$

If T is smaller than a certain threshold value, which is a parameter, then the link will be regarded as undirected. Otherwise, the link is directed pointing from i

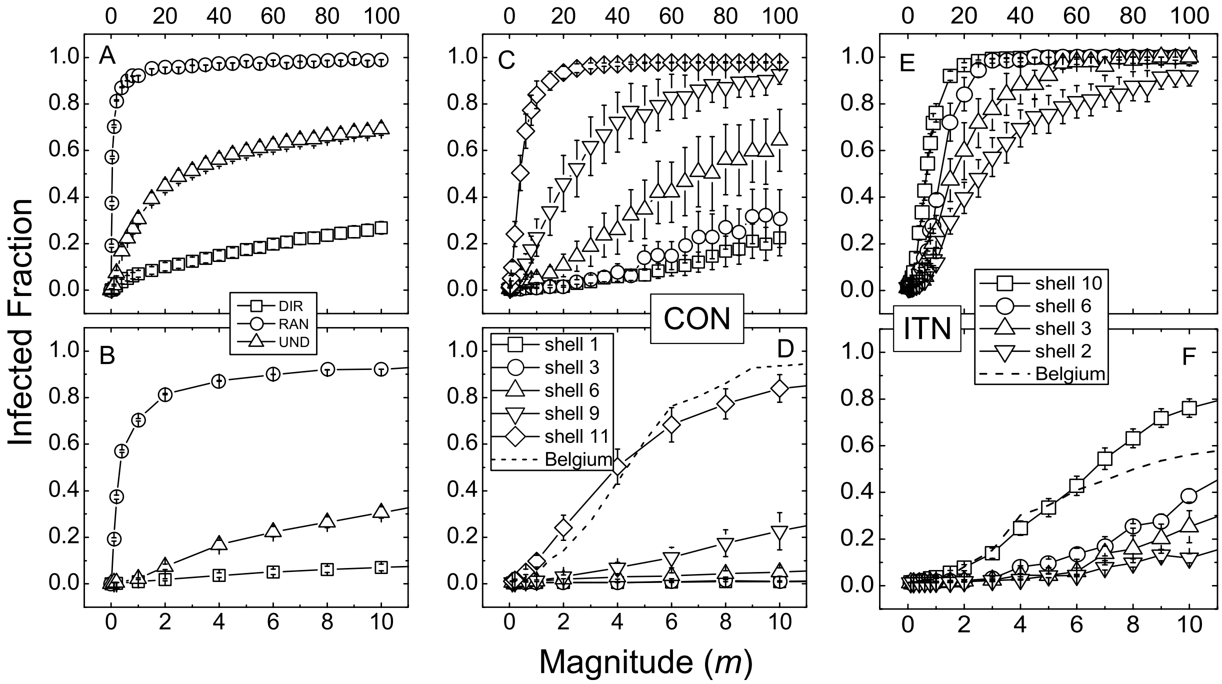

Figure 3. Modelling economic crisis propagation using SIR dynamics. (a) Infected fraction of nodes infected by a crisis spreading versus magnitude m of the crisis. DIR is the real topology of CON, taking into account the directionality, UND is a network similar to the real one but undirected, and RAN is a simulated network with the same number of nodes and the same number of links per node, but with shuffled weights and directions. (b) Zoom of the area showing the spreading for smaller crisis magnitudes m. (c) Fraction of nodes infected by a crisis originating from different shells of the network versus its magnitude m for CON. (d) Zoom of the area showing the spreading for smaller crisis magnitudes m. The dashed line shows the spreading of a crisis originating in Belgium, which is one of the smaller countries that belong to the nucleus of the network. Note that a crisis originating in BE, as m gets larger, becomes more severe in comparison with the average case for all countries in shell 11. (e) Fraction of nodes infected by a crisis originating from different shells of the network versus its magnitude m for ITN. (f) Zoom of the area showing the spreading for smaller crisis magnitudes m. The dashed line again shows the spreading of a crisis originating in Belgium. The results are averages over 50 realizations for each node of the network, and the error bars show the standard deviation.

to j if $w_{ij} > w_{ji}$, and from j to i if $w_{ij} < w_{ji}$. In all cases, the weight of the link is $w_{\text{tot}}^{(ij)} = w_{ij} + w_{ji}$. In the current study, we set the threshold value of T as zero. By increasing this value, we increase the percentage of undirected links in the resulting network, and if we set $T = 1$, then the entire network is undirected. Our results are not sensitive to the value of T. We find that for all values of $T < 0.5$, the crisis epidemic is nearly the same as shown in supplementary figure S4 (available from stacks.iop.org/NJP/12/113043/mmedia).

In figure 3, we present the results of the SIR simulations. Figures 3(a) and (b) show that a crisis propagates to larger parts of the world when it has larger magnitude. Note also that the directed network significantly delays the actual propagation of the crisis, in comparison with the random case (see legend) and with the undirected case. This means that if the directionality were not present, the crisis spreading would be more severe. Figures 3(c) and (d) show how a crisis spreading process in CON depends on different origin countries according to their shell. We find that countries in the nucleus can spread a crisis to larger parts of the world compared to countries in the outer shells, even if the crisis originates in a small country, such as BE. Applying the SIR model to ITN yields the results of figures 3(e) and (f). It is clear that from both figures we draw the same conclusion, i.e. the more inner the shell, the more severe a crisis outbreak originating in this shell will be. Additionally, we show that in ITN a crisis could have more severe effects, since the outer shells are capable of larger global impact in comparison with CON. It is interesting to note that the error bars in figures 3(c)–(f) are small, which means that all of the countries in the shell have similar behaviour, and the shell number determines the spreading rather than the country size. This indicates the predictability power of our method.

In figure 4(a), we show the world countries coloured according to the shell they belong to in CON, and in figure 4(b), we show the countries affected by the economic crisis that started in 2008 in USA, which has spread globally. In figure 4(c), we show a prediction of the model for CON. We simulate an infection of a crisis starting in the US, using $m = 4.5$, which leads to roughly the same percentage of infected countries as the actual crisis of 2008–2009 ($\sim$90% of the world's countries reported economic slowdown due to the crisis). The percentage of correctly predicted countries infected by the crisis using the model is above the average percentage of the prediction using random selection. A quantitative agreement between the prediction power of our model and the actual infection strength is shown in figure 4(d).

Considering the example of BE (ranked 29th according to its total GDP), we find that a crisis originating in this country with magnitude $m = 4.5$ is able to affect for CON almost 60% of the world's countries (average result of 50 realizations), while the worst-case scenario that is given by the maximum value of the fraction of infected countries (out of the same 50 realizations) is 95% of global infection. For a crisis starting in the nucleus of both networks, we find that this maximum fraction has a sharp transition (see supplementary figures S5 and S8 (available from stacks.iop.org/NJP/12/113043/mmedia)), verifying that even crises with small magnitude can propagate to the rest of the world if they originate in the inner shell. This shows the crucial role that these 12 countries play in the world economy. But surprisingly, even countries of intermediate shells may play a major role in crisis spreading. Such countries, as shown in figures 3(c) and (d), are able to spread a crisis with sufficient magnitude to large fractions of the world as well. This is similar to what happened in the case of the Asian currency crisis, starting in Thailand in 1997. Thailand belongs to the $k_s = 5$ shell for CON and to the $k_s = 9$ shell for ITN, but a crisis originating there was able to affect countries of higher shells, and eventually triggered a new crisis that started in 1998 in Russia [21].

3. Discussion

We have modeled the way in which an economic crisis could spread globally, depending on the country of origin. We first created two global networks, which describe strong interaction patterns of the world economy. The first network (CON) is based on the world's largest companies and all of their subsidiaries and links together 206 countries, and the second network (ITN) is created using aggregated trade data linking together 82 countries. A crisis is triggered with a controlled magnitude and propagates from one country to another with a probability that

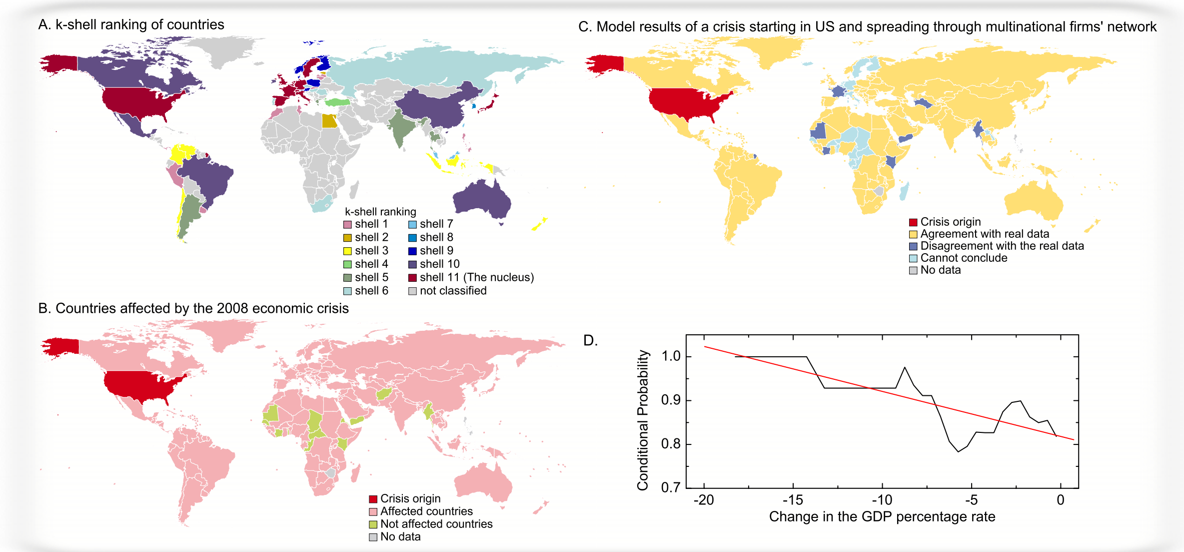

Figure 4. Spreading of a real crisis to the world. (a) World countries coloured according to the k-shell they belong to for CON. (b) Countries affected by the economic crisis that started in the USA in 2008. The effect of the crisis is an economic slowdown, as is reflected by the annual change in the GDP published by the International Monetary Fund. (c) Model results for CON, showing the crisis starting in the USA and spreading to the rest of the world. We performed 1000 realizations, always starting an infection in the USA. For each realization, when the simulation ends, every country has a score = 1 if it is infected and 0 if it is not infected. A sum of the scores per country for all realizations leads to a number inside the interval [0,1000], where 0 means that in all runs this country was not infected and 1000 means that in all runs it was infected. We set a threshold value at 80%, so if a country has a score $\geqslant 800$, then it is considered as infected. If it has a score $\leqslant 200$, then it is considered as not infected, and if it is in the range (200, 800), we say that we cannot determine its status. We find that the average percentage of infected countries is 90.6%, while the worst-case scenario that is given by the maximum number of infected countries in all of our runs is 96.6%. For comparison purposes, if we start a crisis of the same magnitude in countries of lower shells, we find a much lower percentage. For example, if we start the crisis in Russia ($k_s = 6$), the average fraction of infected countries is 3.34%, while the worst-case scenario that is given by the maximum value of the fraction of infected countries is 18.9%. (d) The probability of the correct prediction of the model as a function of the 2009 versus 2008 change in the GDP percentage rate. The curve is smoothed using a six-point moving average. The trend that is shown by the linear fit (red curve) shows quantitatively that the more affected a country is by the real crisis of 2008 (represented by a larger change in GDP), the higher the probability of our model yielding a correct prediction.

depends on the strength of the economic ties between the countries involved and on the strength of the economy of the target country. Furthermore, using the k-shell decomposition method, we are able to identify the role of the different countries in a world crisis, according to the shell they belong to, and we identify the 12 most effective countries for crisis spreading.

We find that although a recent global economic crisis originated in the USA, this might not always be the case and even smaller countries have the potential to start similar crisis outbreaks. In retrospect, we know that this has happened several times in the past (e.g. the crisis in Indonesia), and is happening these days as well, with a crisis in Greece[7] threatening to cause an avalanche effect in other European economies. In part III of the supplementary information (available from stacks.iop.org/NJP/12/113043/mmedia), we examine in more detail the case study of Greece, where we show that the fears of contagion of other major European economies by the Greek crisis are justified. We report almost 40% probability of infection for the major EU countries only through the contagion channels modelled using CON and ITN, i.e. not taking into account the loans that Greece received from other countries. This is in contrast to the common belief that smaller countries partake only in crises that are locally contained but do not spread out to affect the larger countries. Thus, our findings show the predicting power of the network approach using the k-shell ranking methodology. This analysis is important when establishing international commerce rules, policies and legislations, trade treaties and alliances, as they can have a serious impact on monetary policies and international affairs.

Additionally, one could use other techniques based on graph theory in order to identify the backbone of these global economic networks (i.e. extraction of the minimum spanning tree) [4]–[9], or in random matrix theory [22, 23] in order to compare the structure of the real networks against a random network hypothesis. Such complementary approaches could further enhance our understanding of the global economy but are outside the scope of the current work.

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