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Research Paper

Ranking the economic importance of countries and industries

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ABSTRACT

In the current era of worldwide market interdependencies, the global financial village has become increasingly vulnerable to systemic collapse. The global financial crisis has highlighted the necessity of understanding and quantifying the interdependencies among the world's economies; developing new, effective approaches for risk evaluation; and providing mitigating solutions. We present a methodological framework for quantifying interdependencies in the global market and for evaluating risk levels in the worldwide financial network. The resulting information will enable policy and decision makers to better measure, understand and maintain financial stability. We use this methodology to rank the economic importance of each industry and country according to the global damage that would result from its failure. Our quantitative results shed new light on China's increasing economic dominance over other economies, including that of the United States, <u>as well as</u> the global economy.

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Keywords: financial markets; correlations; influence; risk.

A total of five or six keywords/terms are required before your paper can be published. Please provide them on your returned proof.

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1 INTRODUCTION

The growth of technology, globalization and urbanization has caused social and economic activities worldwide to become increasingly interdependent (Battiston *et al* 2016; Havlin *et al* 2012; Helbing 2012; Helbing and Balietti 2010; King 2011; Klimek *et al* 2012; Lazer *et al* 2009; Levy 2010; Lorenz *et al* 2011; Meng and Inomata 2009; Onnela *et al* 2004; Rinaldi *et al* 2001; San Miguel *et al* 2012; Solomon *et al* 2003; Tumminello *et al* 2011; Yamasaki *et al* 2012). From the recent financial crisis, it is clear that components of this complex system have become increasingly susceptible to collapse. The integrated models currently in use have been unable to predict instability, provide scenarios for future stability, control or even mitigate systemic failure. Thus, there is a need for new ways to quantify complex system vulnerabilities as well as new strategies to mitigate systemic damage and increase system resiliency (Farmer and Foley 2009; Lux and Westerhoff 2009). Achieving this would provide new insights into key issues such as financial contagion (Forbes and Rigobon 2001, 2002) and systemic risk (Billio *et al* 2010; Bisias *et al* 2012; Bodie *et al* 2002; Musmeci *et al* 2014) as well as provide a way of maintaining economic and financial stability in the future.

It is clear from the last financial crisis that different sectors of the economy are strongly interdependent. The housing bubble in the United States caused a liquidity freeze in the international banking system, which in turn triggered a massive slowdown of the real economy, costing many trillions of dollars and threatening the financial integrity of the European Union. This demonstrates the high level of dependence between different components in the world economic system. Because strong nonlinearities and feedback loops make economic systems highly vulnerable, we need to understand the behavior of the interacting networks that comprise the economy. How do they interact with each other, and what are their vulnerabilities? Consider an industry in two countries, eg, the electrical equipment industry in China and the United States, and ask yourself which industry is more important to economic stability: that in China or that in the United States? If the production of electrical equipment in China is more critical in terms of global economic stability, when this production is reduced, how will it impact other industries within that country as well as industries abroad?

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To answer these questions, we employ recent advances in the theory of cascading failures in interdependent networks (Buldyrev *et al* 2010; Gao *et al* 2012; Li *et al* 2012). In the case of interdependent networks, a malfunction of only a few components can lead to cascading failures and a sudden collapse of the entire system. This is in contrast to single isolated networks, which tend to collapse gradually (Parshani *et al* 2010). These recent results indicate the central importance of interconnectivity and interdependency to the stability of the entire system. There have been studies of the complex set of coupled economic networks (Garas *et al* 2010; Hidalgo and Hausmann 2008; Huang *et al* 2013; Schweitzer *et al* 2009). However, the importance of countries and industries in the stability of the global economy has not been analyzed, and there is a need for useful methods to rank and quantify their economic importance and influence.

The input–output (IO) model is a technique that quantifies interdependency in interconnected economic systems. Dietzenbacher *et al* (2004) first introduced the IO model in 1951, for which he received the Nobel Prize in Economics in 1973. This model can be used to study the effect of consumption shocks on interdependent economic systems (Isard 1966; Lahr and Dietzenbacher 2001; Leontief 1986; Miller and Blair 2009; Pokrovskii 2011; Santos 2006; Ten Raa 2005). Analysis of IO data is performed using techniques such as the hypothetical extraction method (HEM) (Miller and Lahr 2001; Temurshoev 2010). Although HEM can measure the relative stimulative importance of a given industry by calculating output with and without the industry being examined, it does not quantify each industry's full spectrum of importance to the stability of the global economic system. For example, if an industry in a given country collapses completely due to a natural disaster or civil unrest, it will no longer be able to consume products supplied by other industries. This can cause a cascading failure in the economic system if the other industries cannot function when the cashflow from the failed industry is removed. Here, by measuring how widely the damage spreads, we will rank an industry's importance within the worldwide economic system.

OK to add countries to this sentence and remove later sentence "In this table...", as it was a bit repetitive?

In this paper, we examine the interdependent nature of economies between and within fourteen countries (Australia, Brazil, Canada, China, Germany, Spain, France, the United Kingdom, India, Italy, Japan, Korea, Russia and the United States) and the rest of the world (ROW). We use an IO table (Timmer *et al* 2015) and focus on economic activity during the period 1995–2011. The economic activity in each country is divided into thirty-five industrial classifications. Each cell in the table shows the output composition of each industry to 525 other industries as well as its final demand and export to the ROW (see Timmer *et al* 2015). The IO table contains negative numbers as outputs for various reasons, but their fraction is fairly small and their values are small as well. For simplicity, we set these negative numbers as zero in our analysis. We construct an output network, using the 525 industries as nodes and the output product values as weighted links based on the IO table, and focus on the output product value for each industry.

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Our goal is to introduce a methodology for quantifying the importance of a given industry in a given country to global economic stability with respect to other industries in countries that are related to this industry. Thus, we study the inflow and outflow of money between each set of thirty-five industries and the ROW in each of the fourteen countries (see Section 2 for more detail). We use the theory of cascading failures in

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interdependent networks to gain valuable information on the local and global influence of different economic industries on global stability, a methodology that can provide valuable new insights and information to present-day policy and decision makers.

2 WORLD INPUT–OUTPUT TABLE DATA

The database we use in this paper is the world input–output table (WIOT) of Timmer *et al* (2015). It provides data for twenty-seven European countries, thirteen other countries and the ROW for the period 1995–2011. For our sample, we select the fourteen countries with the largest domestic input and the largest import in production in 2011 as well as the ROW (adding the remaining twenty-six countries into the ROW). Using this sample, we construct a new IO industry-by-industry table. For simplicity, we assume that each industry produces only one unique product. In the WIOT, the column entries represent an industry's inputs and the row entries represent an industry's outputs. The rows in the upper sections indicate the intermediate or final use of products. A product is intermediate when it is used in the production of other products (intermediate use). The final use category includes domestic use (private or government consumption and investment) and exports. The last element in each row indicates the total use of each product. The industry columns in the WIOT contain information on the supply of each product. The columns indicate the values of all intermediate, labor and capital inputs used in production. Total supply of the product in the economy is determined by domestic input plus final demand.

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Based on the supply of the product for each industry, it is possible to construct a directed product supply network. We then reverse the direction of the links in the network (see schematic representation in Figure 1), and the network represents the money outflow from one industry to another in order to purchase materials for production inputs, eg, the electrical equipment industry is pointing to the machinery industry because the electrical equipment industry buys a product from the machinery industry. The links are weighted according to the value of products from the machinery industry to the electrical equipment industry as production input.

3 INDUSTRY TOLERANCE

In order to identify and rank the influence of industries in the stability of this global network, we perform a cascading failure tolerance analysis (Buldyrev *et al* 2010). Our model is described as follows. From the IO table, industry j in country B sells products to industry i in country A and receives \$$x$ million from industry i. Industry j has \$$y$ million as its total yearly revenue. If industry i fails due to a terrorist attack or catastrophic disaster, other industries as suppliers will not be able to sell their products to industry i, and thus the suppliers will lose those revenues. The revenue

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of each industry is reduced by a fraction p', which is the revenue reduction caused by industry j divided by that industry's total revenue: Changes to sentence OK?

$$p'_{\text{country}}(j) = \frac{x(i)}{y(j)}. \tag{3.1}$$

The tolerance fraction p is defined as the threshold above which an industry fails to operate normally due to revenue reduction. (Here, we only consider the condition that triggers an industry with less revenue to meet its financial obligation.) This occurs when the reduced revenue fraction $p'_{\text{country}}(j)$ is larger than the tolerance fraction p. Subsequently, the failure in industry j would cause industries $k, l, \dots, z$ to fail as well. Change OK? Generally, industry n's revenue reduction is the sum of the revenues from the industries that have previously failed, divided by n's total revenue $y(n)$, as shown in (3.2): Changes to sentence OK?

$$p'_{\text{country}}(n) = \frac{x(i) + x(j) + x(l) + \cdots + x(z)}{y(n)}. \tag{3.2}$$

Then, the following simple condition (3.3) is used to decide if industry n can survive in the environment of failures in industries $i, j, k, l, \dots, z$:

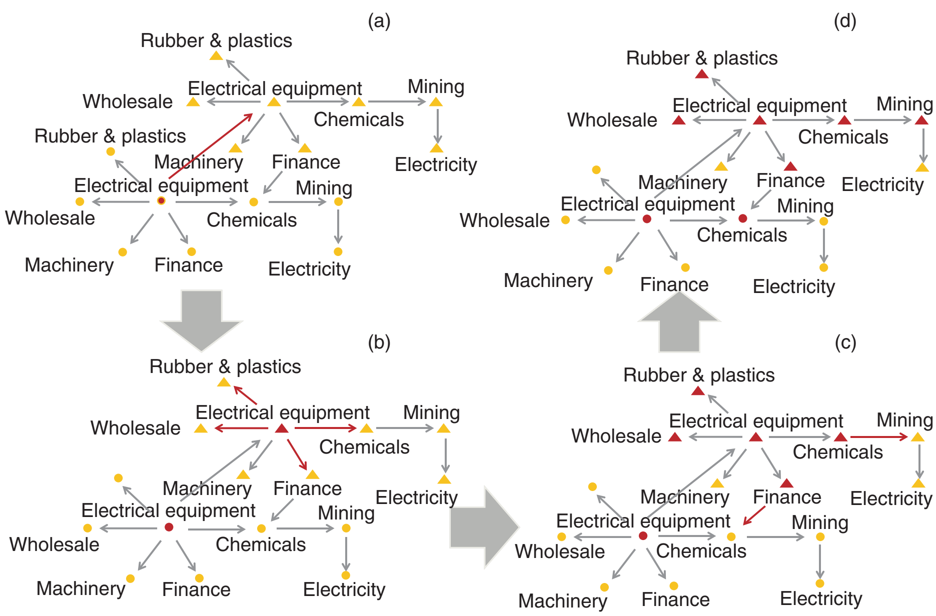
$$\text{industry } (n) \begin{cases} \text{fails} & \text{if } p' > p, \\ \text{survives} & \text{if } p' \leqslant p. \end{cases} \tag{3.3}$$

Here, we assume that (i) p is the same for all industries, and that every industry fails when its $p' > p$; and (ii) the failure of an industry in country A does not reduce the revenue of the other industries in that same country A, because it is able to make a quick adjustment, such as a central government bailout, in order to mitigate the impact to other industries within the country.

The methodology can be schematically illustrated as follows. In step 1, industry i in country A fails. This causes other industries in other countries to fail if their $p' > p$. Assume that in step 2 industries j, k and l fail. The failure of these industries in step 2 will reduce other industries' revenue and cause more industries, including those in country A, to have a reduced fraction $p'(n)$. Thus, in step 3, there is an increased number of industries whose p' are larger than p. Eventually, the system reaches a steady state in which no more industries fail. The surviving industries will all have a reduced revenue fraction that is smaller than the tolerance fraction, ie, $p' \leqslant p$. Figure 1 demonstrates this process, and parts (a)–(d) show the steps in the cascading failure.

To determine how much the failure of each industry would impact the stability of the economic network, we change the tolerance fraction p from 0 to 1 and measure the fraction of surviving industries left in the network. When the tolerance fraction approaches 0, any revenue reduction caused by the failure of one industry can

FIGURE 1 Schematic representation of each step in the cascading failure propagation in the world economic network.



Here, we present an example of two countries, where circle nodes represent country 1 and triangles represent country 2. Both countries have the same industries, and the arrow between two nodes points in the direction of cashflow. In (a), there is a failure in the electrical equipment industry of country 1 (circle) that causes a failure of the electrical equipment industry in country 2. In (b), the failure of the electrical equipment industry in country 2 causes the rubber and plastics, wholesale, finance and chemicals industries in country 2 to fail. In (c), mining in country 2 and chemicals in country 1 fail further. In (d), the network reaches a steady state. The red nodes represent the failing industries and the yellow nodes stand for the surviving industries.

easily destroy almost all the other industries in the network, and the network will collapse. When the tolerance fraction approaches 1, all the industries can sustain a large reduction of revenue, and the failure of one industry will not affect the others.

Figure 2(a) shows the failures of the electric equipment industry in China and the energy industry in the United States for the 2009 WIOT. It also displays the fraction of the largest cluster of connected industries as a function of the tolerance fraction p after the Chinese electric equipment industry begins to malfunction and is removed from the network due to a large shock to the industry. This shock could have a range of different causes, such as natural environmental disasters, government policy changes or insufficient financial capability. The removal of China's electric equipment industry will cause revenue reduction in other industries, because China's electric equipment industry is not able to buy products and provide money to these other industries. When

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p is small, the industries are fragile and sensitive to the revenue reduction, causing most of the industries to fail; the number of surviving industries is very small. When p is large, the industries can tolerate large revenue reduction and are more robust when revenue decreases. In this case, the number of surviving industries tends to increase rapidly at a certain $p = p_c$ value as p increases. Figure 2(b) shows the number of steps that elapse before a stable state is reached as a function of the tolerance fraction p after removing the Chinese electric equipment industry or the US energy industry. The number of steps reaches a peak when p approaches criticality p_c (Parshani *et al* 2010). Change OK?

Here, we analyze for each of the 525 industries this important parameter: the critical tolerance threshold p_c. Our goal is to determine the threshold p_c at which the global network subject to collapse becomes stable and most of the industries in the network survive after initial failures. To this end, we assume that p_c is the critical threshold below which less than 30% of industries survive. When $p > p_c$, more than 30% of the remaining industries survive once the failure cascade in the system is over. When $p < p_c$, the survival rate of the remaining industries is 30% or less. The higher this threshold, the higher the impact of a failing industry will be on the vulnerability of the global network. Without loss of generality, we also take 20–50% of surviving industries to define p_c in simulations. The correlations of p_c values in simulations using different fractions of surviving industries are close to 1. For example, the p_c correlation of 30% and 50% is 1, as shown in the supplementary information. So, choosing 30% of surviving industries to define p_c does not change the relative p_c ranking among industries or the general conclusion. We use this methodology to test how the failure of an individual industry in a given country affects the stability of the entire system. Thus, the p_c of an industry is our measure of the importance of this industry in the global economic network.

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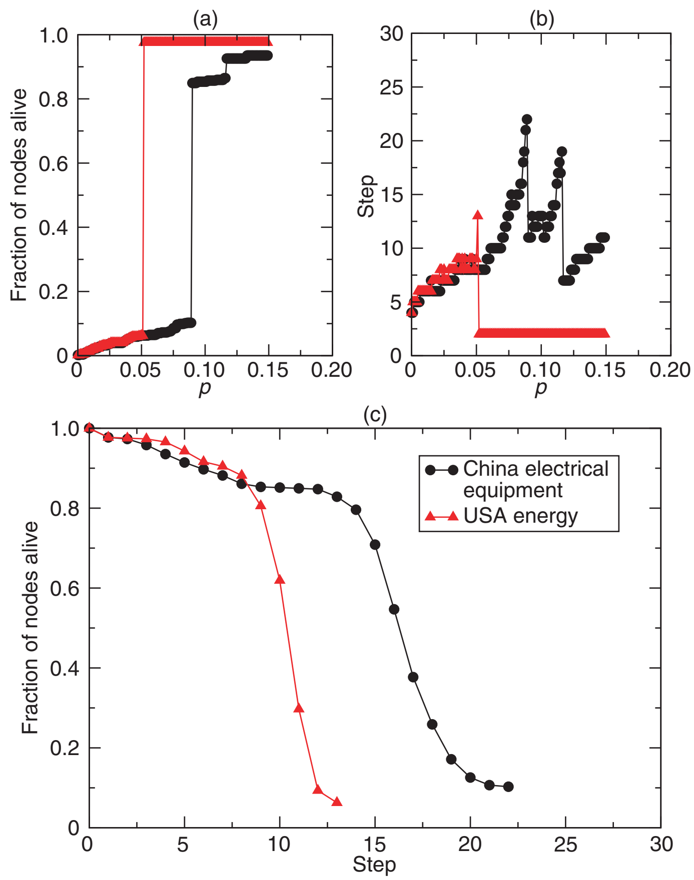
Can we replace this with "online appendix"?

Using the tolerance threshold p_c, we can quantify and rank the economic importance of each industry. We measure the tolerance threshold of thirty-five industries in fourteen countries between 1995 and 2011. We calculate the tolerance of each industry according to how much it affects the entire network, ie, all thirty-five industries in all fourteen countries.

4 IMPORTANCE OF COUNTRY AND INDUSTRY

The proposed methodology provides the means to rank the importance of each industry in the global economic network or the importance of each country in the global economic network.

FIGURE 2 Typical examples of industry tolerance threshold p_c.



The tolerance threshold p_c shows the importance of each industry in the international industry networks. In (a), the black curve shows the fraction of surviving industries as a function of the tolerance threshold for the case where China's electrical equipment industry fails in 2009, while the red curve represents the case of the US energy industry's failure in 2009. In (b), the number of failure steps as a function of p corresponding to (a) is shown. The total number of steps is the number of cascades it takes for the network to reach a steady state after certain initial failure. The peaks in (b) correspond to the abrupt jumps in (a), which means the large numbers of cascade steps at p_c are associated with dramatic failures in the industry network. Each step in the cascading process in (b) is demonstrated in Figure 1. Finally, (c) shows the fraction of nodes alive as a function of failure steps. The thresholds p are 0.089 and 0.051 respectively, which are close to the critical p_c in both scenarios.

We define the importance of each country by averaging the thirty-five industries p_c within the country for a specific year,

$$I_{\text{country}}(i) \equiv \frac{1}{n}\sum_{k=1}^{n} p_c(i,k), \tag{4.1}$$

where n is the number of industries. To rank the importance of a given country, we average the largest four tolerances of industries for each country as an illustration, as shown in (4.1).

Figure 3(a) shows the importance of all countries for different years where the average in (4.1) is taken over the four largest p_{c} values, in order to consider the strongest industries. It is important to note that the ROW is the most important "country", since it includes many countries aside from the fourteen countries included in the sample. Countries in the ROW provide products that are crucial inputs to these fourteen countries and their industries. We also define the importance of the individual industries in terms of the average of their p_{c},

$$I_{\mathrm{industry}}(i) \equiv \frac{1}{T} \sum_{j=1}^{T} p_{\mathrm{c}}(i, t), \tag{4.2}$$

where T denotes years. Figure 3(b) shows the average tolerance of the industry over all years (1995–2011) for individual countries. For simplicity, we plot only the top twenty industries with respect to the average of I_{industry} values for all the countries. Note that the electrical equipment industry is the most important when we average the tolerance fraction p_{c} across seventeen years. The energy industry p_{c} in the United States, for example, is relatively high because the United States is the world's largest energy consumer.

5 ROBUSTNESS AND STABILITY OF ECONOMIC STRUCTURE

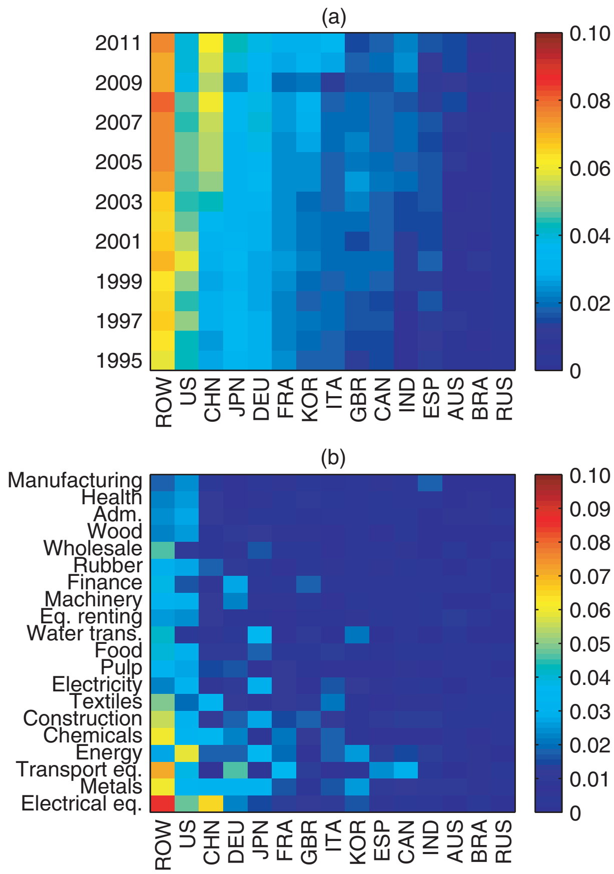
We use the critical tolerance threshold p_{c} to measure the importance of each industry in the global economic network. We can also rank each industry according to its tolerance $p_{\mathrm{c}}(i, k)$ for each separate country, ie, the tolerance of industry i in country k. By comparing industry order rankings for different years, we can study the similarity in economic environment across a period of seventeen years.

To do this, we use the Kendall τ coefficient (Kendall 1938), which measures rank correlation, ie, the similarity in data orderings when ranked by each quantity. Let $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$ be a set of observations of the random variables X and Y, respectively. Any pair of observations (x_i) and (y_i) is concordant if the ranks for both elements agree, that is, if $x_i < x_j$ and $y_i < y_j$, or if $x_i > x_j$ and $y_i > y_j$. Otherwise, the pair is discordant. If $x_i = x_j$ or $y_i = y_j$, the pair is neither concordant nor discordant. The Kendall τ coefficient is defined as

$$\tau = \frac{n_+ - n_-}{\frac{1}{2} n(n-1)}, \tag{5.1}$$

where n_+ is the number of concordant pairs and n_- is the number of discordant pairs. The coefficient τ is in the range $-1 \leqslant \tau \leqslant 1$. When the agreement between the

FIGURE 3 Ranking the importance of individual industries or countries.



(a) Map of averaging industry tolerances for each country, I_{country}. The average tolerance p_{c} is calculated by averaging the largest four p_{c} for each country in one year. The color represents the strength of the tolerance, ranging from blue (low tolerance) to red (high tolerance). (b) Averaging industry tolerance over seventeen years (1995–2011). The average tolerance p_{c} is calculated by averaging the industry tolerance over seventeen years for each country (for simplicity, we plot only the top twenty industries with respect to their I_{industry} value). The values are represented using the same color code as in (a).

two rankings is perfect, the coefficient is 1. When the disagreement between the two rankings is perfect, the coefficient is -1. If X and Y are independent, the coefficient is approximately 0.

We use the Kendall τ to investigate the evolution of the economic structure of each country in our sample. For each year, we rank the industries in each country according to their tolerance values and calculate the Kendall τ for every year pair. Figure 4

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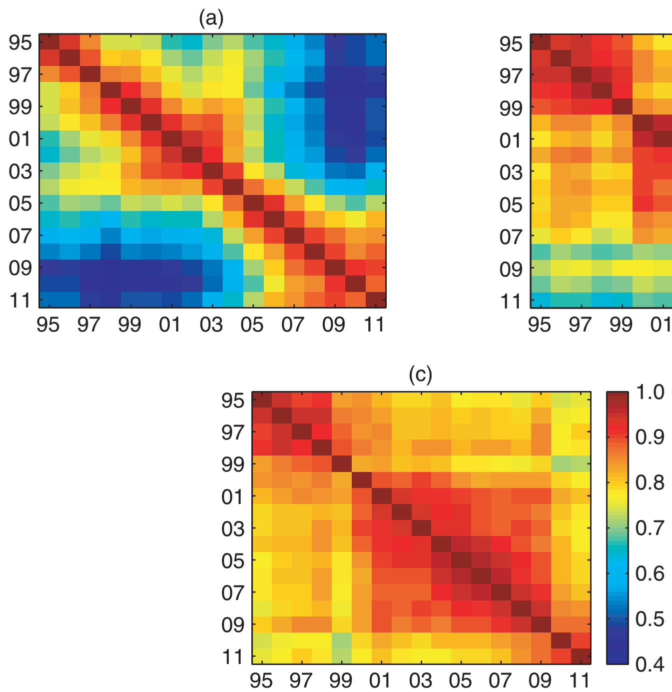
FIGURE 4 Kendall correlation coefficient heat map showing the industry rank correlation coefficient between every pair of years from 1995 to 2011.



Using the Kendall correlation coefficient τ, we investigate the evolution of the economic structure of the investigated countries. For each year, we rank the industries in each country according to their tolerance values. We then calculate the Kendall τ for every pair of years and plot the values for (a) China, (b) the United States and (c) Germany using a color code ranging from blue (low similarity) to red (high similarity). See the online appendix for all other countries.

shows the values of the Kendall τ for all pairs of years, for China (Figure 4(a)), the United States (Figure 4(b)) and Germany (Figure 4(c)), using a color code ranging from blue for low similarity to red for high similarity (see the online appendix for all other countries). Changes to sentence OK? For these three countries, we find different behaviors in terms of the stability and consistency of the economic structures. In the case of China, we observe that the structure changes significantly, with high values of the Kendall correlation (represented using red) only presenting for the previous 2–3 years (as can be observed from the diagonal of elements of Figure 4(a)). Change OK? However, in the case of the United States, it is possible to observe three distinct periods in terms of the stability of the economic structure: 1995–99, 2000–2007 and 2008–11 (see Figure 4(b)). Word added – OK? The first marks the period leading into the "dot.com crisis", which was followed by a significant change in US market structure. The second marks the period leading into the global financial crisis, which again was followed by a significant change in US market structure. The third marks the period following the global financial crisis, which shows no stable period in terms of market structure. Finally, in the case of Germany, we observe only two periods: 1995–99 and 2000–2011 (see Figure 4(c)). The first period can also be attributed to that apparent in the case of the United States; however, the effects of this were probably felt to a lesser extent than in the United States, in part due to the introduction of the euro at that time. Interestingly, we do not observe a change in German market structure following the recent financial crisis, which highlights the degree of stability in the German economy.

"the looming dot.com crisis"? Changes to rest of sentence OK?

6 THE RISE OF CHINA

Due to the fact that economic influence is dynamic across time, we ask whether the methodology presented here can provide new information on the increase or decline of economic importance. For each year, we calculate the individual industry tolerance as described above. We then calculate the average tolerance of each country for a given year. Figure 5 shows the average of p_c for each country during the seventeen-year period investigated. In Figure 5(a), we show the largest tolerance p_c in China, the United States and Germany over seventeen years. Figure 5(b) shows the average of the four largest industries' p_c, while Figure 5(c) shows the average of the eight largest p_c in each country.

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We find that the average tolerance p_c of China becomes larger than that of the United States after 2003, which is most pronounced in Figure 5(b). The US tolerance p_c first increases from 1995 to 2000, and then decreases from 2000 to 2009, with a slight increase in 2010–11. Germany's tolerance p_c generally increases in the investigated period and shows certain fluctuations between 2000 and 2005. Note that for the United States the change across time is minor, but the economic importance of China increases significantly. The economic importance of China relative to that of the United States shows a consistent increase from year to year, illustrating how the economic power structure in the world's economy has changed over time.

To further validate these results, we compare the total product output (see Figure 6, red triangle) and average tolerance p_c (see Figure 6, black circles) for China, the United States and Germany as a function of time. The product output (see Figure 6, red triangle) value is the total cashflow a country supplies to other countries plus value added in products, which also indicates its total trade impact on foreign countries. Studying Figure 6, we find that, generally speaking, the total outputs of the three investigated countries grow over time, with those of the United States and China being higher in value than that of Germany (see Figure 6, right y-axis). However, by comparing the tolerance p_c, we find three different behaviors. First, in the case of China (Figure 6(a)), we find that both the tolerance p_c and total outputs increase in

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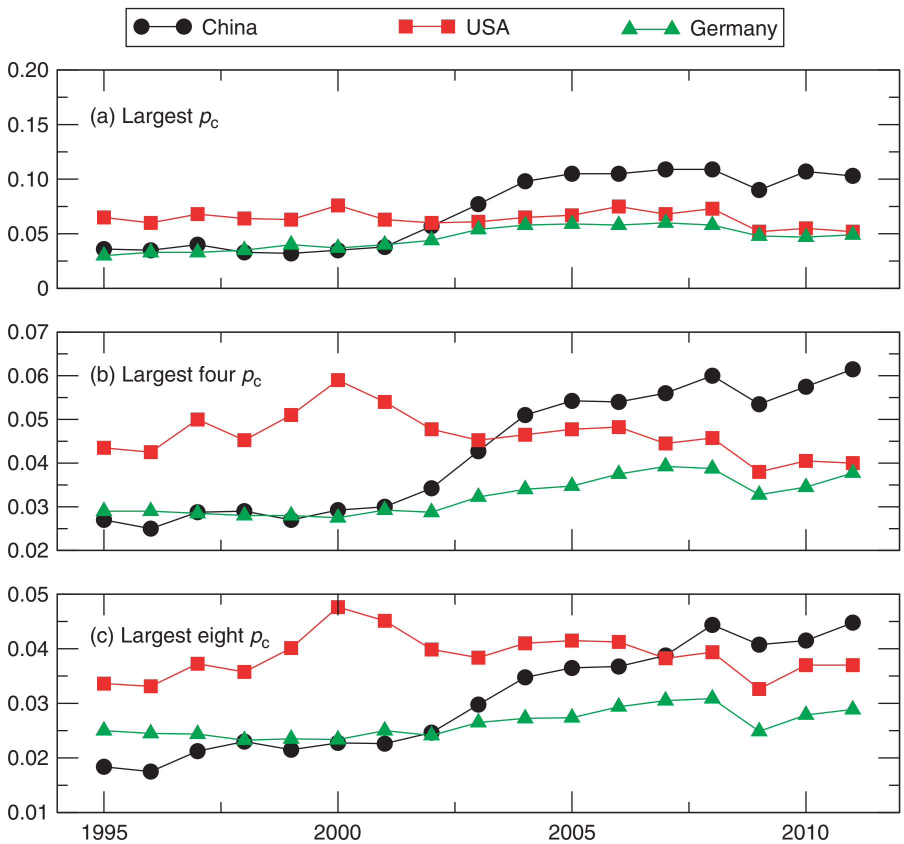
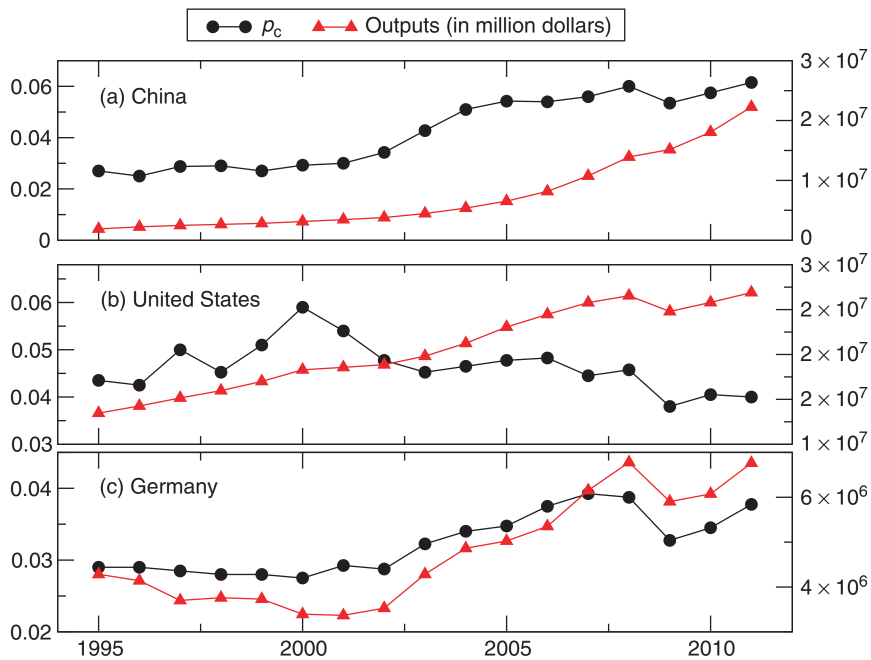
FIGURE 5 Tolerance p_c changes in China, the United States and Germany over seventeen years.



We show that the average tolerance p_c increases from 1995 to 2011. (a) The largest tolerance p_c in China, the United States and Germany over seventeen years. (b) The average of the four largest p_c in each country. We can see the p_c of China becomes larger than that of the United States after 2003. (c) The average of the eight largest p_c in each country. The difference between the average p_c of China and that of the United States is smaller compared with that shown in (b) for 2005–11. This is because the average includes more industries with small p_c and mainly the importance of large industries increases. The US tolerance p_c first increases from 1995 to 2000, and then slightly decreases from 2000 to 2009, with a small increase in 2010–11. In general, Germany's tolerance p_c slightly increases during the seventeen-year period, showing small fluctuations between 2000 and 2005.

time. We also observe that in the early 2000s there was a jump in the tolerance p_c, followed by a sharp increase in the total output. Second, in the case of the United States (Figure 6(b)), we find that while the total output is increasing in time, the tolerance p_c exhibits a decreasing trend. Finally, in the case of Germany (Figure 6(c)), we find Change OK?

FIGURE 6 Tolerance p_c of China, the United States and Germany compared with total product output value.



For each country, p_c is the average of the largest four industries' p_c in that country (black circles). The product output (red triangle) value is the cashflow a country supplies to the rest of the countries, which also indicates its effect on foreign countries. In (a) and (c), the trends of the p_c and output value are similar, which indicates China and Germany are becoming more influential on the world economy. In (b), the p_c of the United States increases in the period 1995–2000, and decreases from 2000 to 2011, while the output value generally increases from 1995 to 2011.

that while the total import is increasing in time, the tolerance p_c is rather stable with small fluctuations.

This provides further evidence of the change in influence of these three important economies: that of China is increasing, that of the United States is declining and that of Germany is generally constant across time. Comparing the total output with the tolerance p_c provides further evidence that the tolerance measurement of a country's impact reveals the underlying economic evolving dependencies, which is not obvious from the simple measurement of total output capability.

7 CONCLUSIONS

We have developed a framework to quantify interdependencies in the world industrial network and measure risk levels in global markets. We used our methodology to rank the economic importance of each industry and country according to the global damage that would result from their failures. Using network science to investigate IO data of cashflows between different economic industries, it is possible to stress test the global economic network as well as identify vulnerabilities and sources of systemic risk. Our quantitative results shed new light on China's increasing economic influence over other economies, including the United States. The resulting information will enable policy and decision makers to better measure, understand and maintain financial stability.

DECLARATION OF INTEREST

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Repetition of 'EU project' OK in this list? Clarify?

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