To Trade or Not to Trade: Analyzing How Perturbations Travel in Sparsely Connected Networks

Marshall A. Kuypers[1,2], Walter E. Beyeler[1], Matthew Antognoli[1,3], Michael D. Mitchell[1], and Robert J. Glass[1]

[1] Complex Adaptive System of Systems (CASoS) Engineering
Sandia National Laboratories, Albuquerque, New Mexico, USA
{mkuyper,webeyel,mantogn,micmitc,rjglass}@sandia.gov
http://www.sandia.gov/CasosEngineering/
[2] Management Science and Engineering Department, Stanford University
Stanford, California, USA
mkuypers@stanford.edu
[3] School of Engineering, University of New Mexico
Albuquerque, New Mexico, USA
mantogno@unm.edu

Abstract. In global economics, nations are often faced with the opportunity to open or close new avenues of trade or to join new markets. These actions can be beneficial or harmful for a nation because entering a market exposes that nation to the perturbations caused by others in the market. However, joining a new market offers the benefit of lower prices and increased security against domestic perturbations because shocks are spread across all trading partners. This risk/benefit tradeoff is relatively straightforward for one market, but the effects are more complicated when multiple markets are introduced. We use an agent-based model to analyze how the connection pattern of markets affects perturbations that travel across networks. We find that shocks are not easily transmitted across networks unless the perturbed resource is directly traded and we discuss the tradeoffs associated with opening new international market connections.

Keywords: Complex adaptive systems, Agent-based model, Trade, International markets, Perturbations, Industry protection.

1 Introduction

Although international transactions are a significant portion of nearly every nation's economy, the dynamics of trade are still only partially understood. The incentives and politics of trade have been studied without uncovering a complete picture of the optimal strategy for choosing a trading network. Furthermore, the complicated relationships and feedbacks among trading entities often lead to surprises for policy makers. Understanding international transactions is important because trade opens up avenues for improved efficiency but also makes the nation vulnerable to supply shocks.

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In this paper, we describe an agent-based model (ABM) designed to study resource exchanges between economic agents. We initialize a simple system consisting of two nations and observe how perturbations travel across sectors and between nations. We find that shocks are not transmitted easily between nations unless the resource produced by the perturbed sector is internationally traded. If the perturbed resource is internationally traded, the consuming sectors experience gains and losses that are determined by the global connection pattern of markets.

1.1 International Relations and Trade as Complex Systems

While many researchers have modeled supply chains and organizations as complex adaptive systems (CAS) there has been very little work on international relations modeled as CAS [1, 2]. Axelrod's work in the 1990s proved complex systems are a useful perspective for analyzing international relations (IR), but almost 20 years later the IR community has yet to embrace CAS techniques even though IR problems contain many of the CAS criteria outlined in Choi et al. 2001 such as interacting agents, nonlinear relationships, and adaptive components [3, 4, 5].

Contagion, or the spread of economic shocks between countries, is one of the few processes that has been understood using CAS theory [6]. However, most of the literature on contagion is limited to finance, with little attention paid to commodities or goods. The interest in contagion started in the late 1990s when a financial crisis in East Asia spread to South America but it has gained more prominence in the last five years after the financial collapse of 2008 and the current Eurozone crisis [7, 8]. Others have studied how shocks in industries such as airlines travel between international economies but this work is very sparse [9]. Our work broadly studies the tradeoffs with opening new avenues of trade and shows another example of applying CAS modeling to IR problems.

2 Model Formulation

We use an agent-based model developed at Sandia National Laboratories to analyze this system [10]. The agents are defined by a set of coupled nonlinear first-order differential equations and interact through trading events, resulting in continuous behavior that triggers discrete exchanges.

Each agent is called an entity. Each entity must consume, produce, and store resources to remain competitive in its environment. A 'health' state variable controls the agent's production processes and is a function of the agent's resource consumption rates. The nominal level of health is 1 and higher health levels are caused by above-nominal consumption rates. Low health levels are caused by agents reducing consumption due to low demand for its product, high input prices, or low money levels. Protracted reduction in consumption can cause an agent to die although this did not occur in the scenarios examined in this study.

Agents interact in discrete exchange events that are facilitated by markets. Each agent buys and sells resources in a market and is matched for trading using a double auction. A collection of agents and markets makes up a nation. The specific representation of this hierarchical structure is irrelevant and can represent a variety of institutions, such as companies, industries or nations.

Each agent processes resources to remain competitive in its environment. Agents obtain resources at a market and store them. Then a production process occurs, converting the input resources to an output resource. The output resources are stored in an output tank before being sold at a different market.

Perturbations are introduced into the model by removing a defined amount of resource from an agent's output storage tank which causes the agent to readjust its production and consumption as it balances the competing interests of filling its storage tank back up and selling its produced resource to obtain money. The resulting behavior affects other agents and the shock propagates through the system. For these simulations we chose a set of parameter values where the perturbation propagated through the production network but did not cause any agent to die.

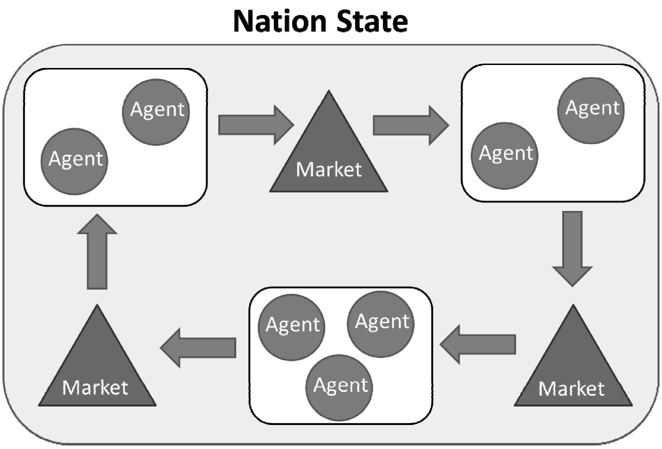

Fig. 1. A nation's structure. Agents are circles, rectangles are sectors, and triangles are markets. A collection of agents, sectors, and markets makes up a nation.

For this study, we initialize two identical nations, A and B. Each nation has six sectors made of one agent each. The sectors are fully connected within the nation so that each sector consumes resources from every other sector and produces a resource that every other sector needs (figure 2). This model can be interpreted as representing a closed system of several resources such as food, water, goods, energy, and labor. Each sector requires a non-zero amount of every other resource although some substitution of resources is possible. Our model assumes the resource requirements are symmetric for each sector but we have the flexibility to represent realistic asymmetric trade flows, which we would like to study in the future.

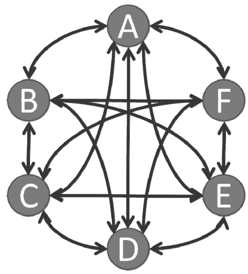

Fig. 2. The structure of the network for each nation. Each lettered node is a sector made up of a single agent. The network is fully connected. A study on how network structure affects the dynamics of the systems can be found in Kuypers et al. 2011 [11].

We study the effect of international markets that allow trade between two nations. There is no additional cost imposed on international markets, resulting from geographic proximity although this feature will be implemented in the future. Geographic constrains might create more realistic behavior by imposing a transportation cost which would incentivize domestic trading over international.

We introduce perturbations by removing the entire product inventory of a resource (F) in nation A and observe the changes in health in all sectors in both nations. The total impact of a perturbation is measured by integrating the difference in health between a perturbed run and an unperturbed run where the system maintains an equilibrium health level equal to one for the total duration of the simulation.

3 Perturbations in Non-internationally Traded Markets

First, we consider perturbations that are only indirectly spread through nations, meaning the perturbed resource is not internationally traded. If the number of internationally traded markets is increased, thereby increasing the number of connections between the two nations, then perturbations travel more easily from nation A to nation B. In figure 3, we expect to see a larger response in case 2, since more connections are available.

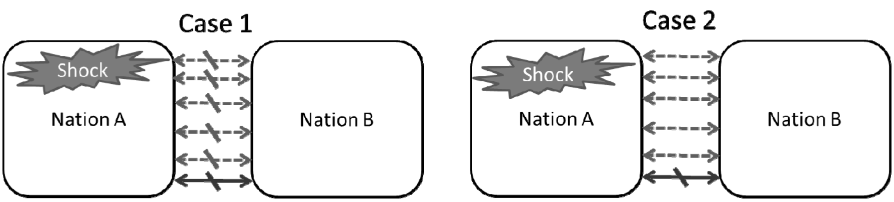

Fig. 3. Dashed arrows denote markets in non-perturbed resources and solid arrows denote markets in the perturbed resource. An uninterrupted line means that resource is internationally traded while a break-line means that the resource is not internationally traded. Case 1 shows no resource internationally traded, while case 2 shows 5 resources (all except the resource produced in the perturbed sector) internationally traded. Shocks are introduced in nation A.

Indeed, Table 1 shows that the perturbation travels to the second nation state more easily when there are more international markets. Furthermore, as more markets are opened nation B reaps an increasing health gain and nation A sees an increasing health loss. When a perturbation causes a price spike in a closed nation, the perturbed sectors recover part of their losses by selling their resources for high prices. When international markets are open, nation B's sectors benefit from the increased price which delays the recovery of the perturbed nation's sectors.

The total system impact, meaning the net health impact for nations A and B summed together, is constant regardless of the number of international markets. The consistency of the perturbation impact is not obvious because the total health loss could rise as more of the perturbation leaks into the new nation which is initially in equilibrium. Although more of the perturbation travels from nation A to nation B, the total system impact does not change; only the distribution of gains and losses changes.

Table 1. Health values as a function of the number of international markets in non-perturbed resources. The error term is the estimated standard deviation calculated from three runs.

Number of International Markets in Non-Perturbed Resources	Net Health Impact of Perturbed Nation (Nation A)	Net Health Impact of Un-Perturbed Nation (Nation B)	Total Health Impact (nation A + Nation B)
0	-12.27 ± 0.06	-0.02 ± 0.00	-12.29 ± 0.06
1	-12.29 ± 0.10	-0.08 ± 0.06	-12.37 ± 0.08
2	-12.94 ± 0.26	0.36 ± 0.09	-12.58 ± 0.29
3	-13.23 ± 0.05	0.84 ± 0.02	-12.38 ± 0.05
4	-13.83 ± 0.12	1.31 ± 0.08	-12.52 ± 0.07
5	-14.11 ± 0.17	1.70 ± 0.05	-12.41 ± 0.22

Nation B only experiences a net impact that is 15% the magnitude of nation A's response when all the non-perturbed markets are internationally traded, showing that shocks cannot travel efficiently through markets that are not directly perturbed. Small shocks are dampened by the relationship between inputs and outputs. For example, a small shortage of tires causes a car manufacturer to pay a higher price for tires, but the company still continues to produce cars. Therefore, therefore, the price of cars remains relatively stable since the same number of cars is produced before and during the shock. However, a larger shortage of tires causes the car manufacturer to limit production because it cannot get enough tires for all its cars. Small shocks do not propagate though sectors because only large shocks cause the production to be affected enough to cause another resource shortage.

4 Perturbations in Internationally Traded Markets

Shifting attention to cases where the perturbed resource is internationally traded provides new insights. First, we can look at the net health impact as we increase the number of international markets. The connection pattern is illustrated in figure 4.

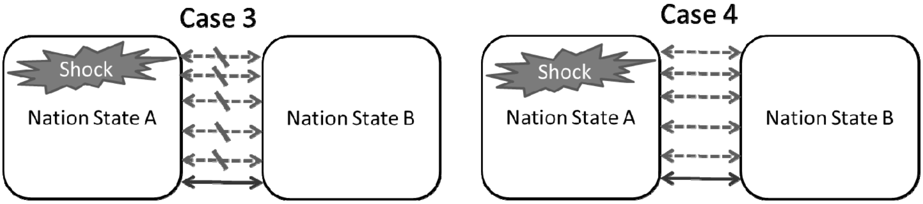

Fig. 4. Case 3 and case 4. The resource produced by the perturbed sector (the solid line) is internationally traded. Other international markets are opened (dashed lines). Case 3 has one international market, and Case 4 has all resources traded internationally.

Case 3 becomes case 4 by introducing additional markets. The total system health impact is shown in figure 5. Allow the perturbed resource to be traded internationally causes a significantly worse total system impact than an isolationist strategy. However, the total system impact becomes less severe as more international markets are added. Trading internationally becomes the optimal choice once 2/3rds or more of the markets are traded internationally.

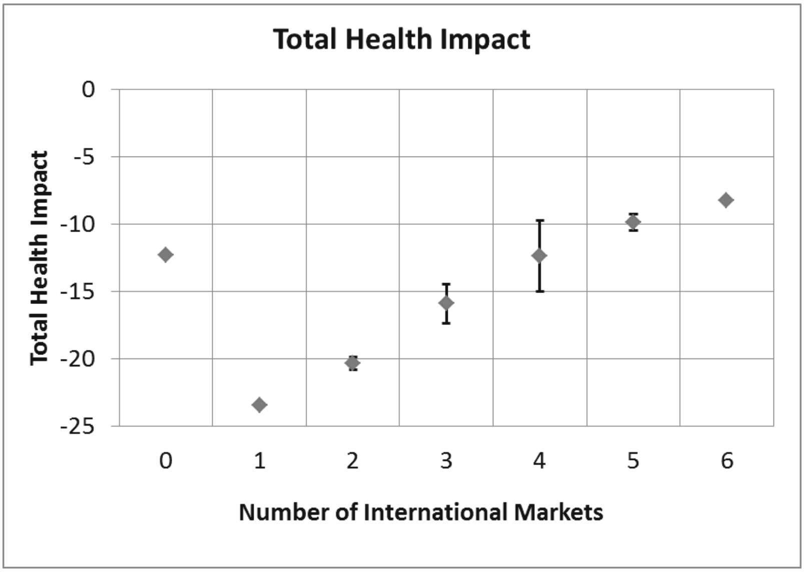

Fig. 5. Total health impact for nation A and B as a function of the number of international markets. The first market to be opened to international trade is the resource produced by the perturbed sector. Error bars show the estimated standard deviation based on three runs.

At the scale of the individual nations, we see a different story. For the non-perturbed nation, the non-perturbed sectors (A-E) follow two trend lines depending on whether they are internationally traded. An internationally traded project always causes a sector's health to decrease in comparison to not trading internationally because the sector is underbid by the corresponding sector in the unperturbed nation. The response transitions between the two trend lines when the sectors become traded internationally. Additionally, the perturbed sector follows its own trend, which grows monotonically.

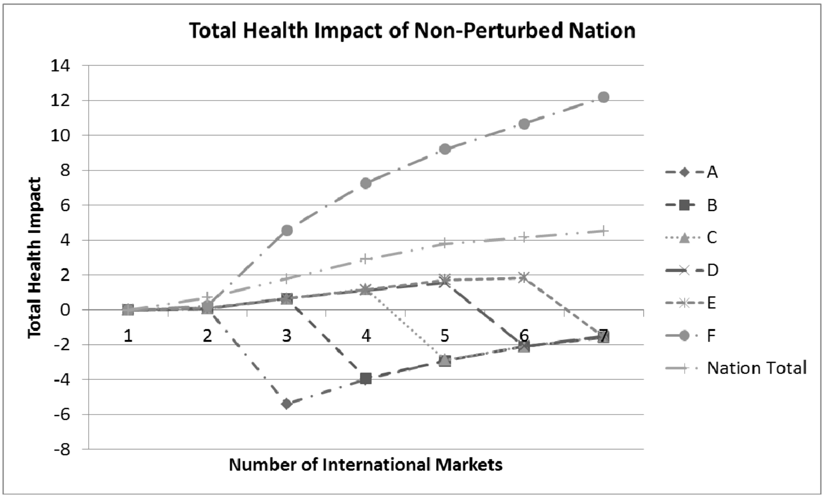

Fig. 6. Total health impact for the non-perturbed nation. Market F is the first internationally traded market, and then A through E are brought in sequentially.

The response for the perturbed nation is similar to the non-perturbed nation, but with the trends reversed. Figure 7 shows the total health impact as the number of international markets increases for both the perturbed nation and the unperturbed nation. The two responses are opposite.

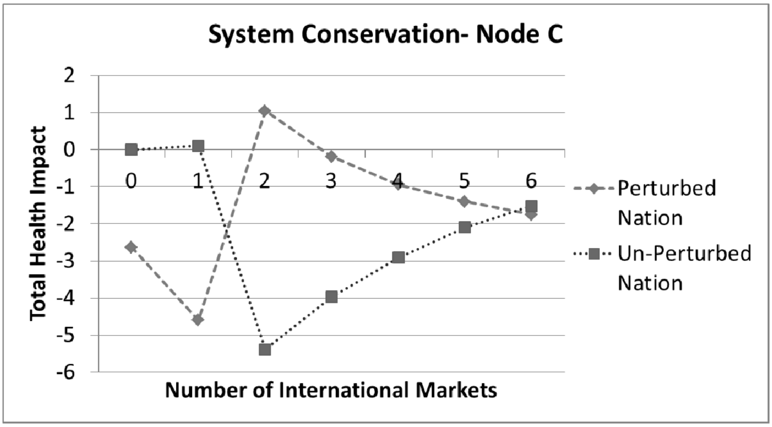

Fig. 7. System conservation for node C. Note that node C behaves inversely between the two nations.

4.1 Perturbation Flows

Many of the model's dynamics are characterized by universal trends, but significant qualitative changes occur as well. The model responds qualitatively differently depending on whether the perturbed sector is internationally traded or the perturbed sector plus one non-perturbed sector is traded internationally.

The model output is similar to two closed nations when only the perturbed sector's output is traded internationally,. The perturbation does not travel between nations very effectively through one sector alone. Once another sector is added the perturbation travels through the nations much more. The requirement to have two international markets to transmit shocks can be understood by considering water flow. When two tanks of water are connected by one pipe which is pressurized, nothing too interesting happens. Some water flows from the first tank to the second tank, but the pressure in the second tank will quickly build, preventing more flow through the pipe. Adding another pipe causes a return flow of water, which allows more water to flow through the first pipe. This creates more interesting dynamics.

Similarly, in the model, a single connection is not enough to transmit an economic shock. A return mechanism is required for the two systems to affect each other. The return mechanism is a second international market.

4.2 Time Series Analysis

Examining a single perturbation and how it travels from one nation to another reveals some important dynamical processes of the model. Figure 8 shows the response when only the perturbed sector is internationally traded. First, the resource is removed. Immediately, the perturbed sector's health falls because it has no resource to sell, which causes its money level to drop and it scales back consumption. Additionally, all the sectors in the perturbed nation experience a health loss. Although the perturbed nation's sectors can still obtain input resources in the international market, the perturbed sector F is not consuming resources they produce. Therefore, the health loss of the non-perturbed sectors results from the reduction in demand for their output, not because of a shortage of any input resource. The perturbed sector in the non-perturbed nation is able to benefit slightly from the additional demand for its product causing it to gain money and increase consumption, which gives more money flow to the other sectors in its nation, resulting in a slight health gain.

These processes continue until the perturbed sector resumes selling its resource. After the perturbation, the perturbed agents have competing interests to build up their storage tank and accept the high price being offered for its goods. Once the price is high enough and the input tank level is high enough, the agent starts to sell and begins to make profits resulting in higher money levels, which spurs additional consumption. Once the health values have reached their extrema the trends reverse. The perturbed sector starts producing again and benefits from the high price of its good. It increases consumption which allows the other sectors in its nation to recover also. The increased consumption and production rates provide some momentum so that the perturbed sector reaches the maximum health of any sector before the perturbation is damped out.

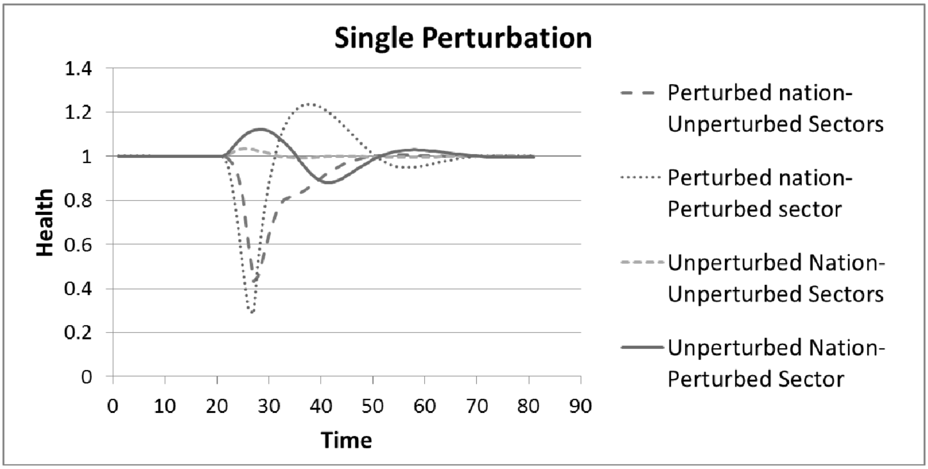

Fig. 8. Time series for a single perturbation on nation A, where the perturbed sector is the only internationally traded market. The time series are classified by their nation and sector.

These processes lead to an interesting result. When a perturbation occurs, there is not a net flow of resources into the hole that is created. There is a flow of resources away from the hole created by the perturbation. The agents find the best market, which is far away from the shock. For example, if you sell apples in a town where a tornado hits, it makes sense to leave and go to a town where there is still demand for apples.

5 Discussion

The applications of this study are far reaching. Our model points to interesting tradeoffs due to connections in international markets. Many developing countries practice industry protection where they shield a developing sector to allow it to become strong enough before entering the international market [12]. For example, it is unlikely an Indian car manufacturer could compete with the Japanese, European, and American auto makers. Therefore, the Indian government might create incentives for consumers to buy the Indian product and discourage foreign suppliers by capping imports or setting tariffs. Of course, this can also stifle innovation and turn out worse if the protected company decides it does not need to compete or innovate. Industry protection is still a hotly debated topic, with numerous studies offering data supporting its adoption and denouncing it [13, 14, 15]. This paper is not an argument for or against industry protection but instead points out some interesting features that result from different trading structures.

This work shows that it is not obvious who will win and who will lose from a given perturbation. Nations should consider feedback effects carefully when protecting industries.

5.1 Pushing the System to Complexity

The system may not currently be displaying complexity, since we have a low number of homogenous agents. We would like to scale these simulations up to include more realistic trading patterns, more realistic network structures, and heterogeneous agents. New emergent behaviors might become evident under these conditions.

6 Conclusion

In this paper, we present an ABM of two idealized nations that trade resources using several exchange patterns. We observe how the pattern of international connections affects a nation's response to a shock. We find that perturbations do not travel across nations efficiently if the perturbed sector is not internationally connected since the unperturbed sectors absorb a significant amount of the shock and only transmit it if the price shock is large enough to disrupt their production.

We also find that when the perturbed sector is not internationally traded the total system impact is unaffected by additional international markets. However, if the perturbed sector is internationally traded, then additional international markets reduce the net system impact. In both cases the distribution of winners and losers changes based on the connection pattern.

When a perturbation occurs the goods flow toward stronger economies instead of rushing in to fill the void left by the shock. Agents seek to preserve their markets and move to where their goods can demand higher prices which is away from the perturbation.

Our work shows how nations might evaluate their trading network and offers some insights into the industry protection argument. Complicated feedbacks lead to gains and losses across sectors and nations that are not intuitive.

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