The Crossover Point: Comparing Policies to Mitigate Disruptions

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Abstract. Companies, industries, and nations often consume resources supplied by unstable producers. Perturbations that affect the supplier propagate downstream to create volatility in resource prices. Consumers can invest to reduce this insecurity in two ways; invest in and impose security on the suppliers, or can invest in self-sufficiency so that shocks no longer present devastating consequences. We use an agent-based model of a complex adaptive system to examine this tradeoff between projecting security and investing in self-sufficiency. This study finds that the significance of tradeoffs correlates with the dependence of the consumer on the supplier.

Keywords: agent-based modeling, complex systems, projecting security, self-sufficiency, trade.

1 Introduction

Unstable nations often control critical resources. Iraq and Nigeria are large oil exporters and the Democratic Republic of the Congo contains reserves of cobalt, gold and copper [1]. Other unstable regions contain deposits of heavy metals used in computer chip manufacturing. Trade agreements between an economically-stable nation and an unstable nation are risky. Instability in producing countries can cause disruptions in supply leading to volatility in resource prices. Stable countries have an interest in encouraging the stability of their trading partners. The United States has historically maintained a military presence in the Middle East to secure the oil fields of its trading partners. Recently, nations are giving more consideration to another option for securing resources. Consumer countries are investing in technologies to develop more efficient native production of critical resources, reducing the need to import from unstable countries. The U.S. is investing in alternative sources of energy,

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and photovoltaic manufacturers are studying new materials that could replace rare heavy metals. Analyzing the costs and benefits associated with protecting unstable suppliers and those with investing in self-sufficiency can aid in designing effective policies that lower resource cost and increase resource security.

We present an agent-based model that represents resource exchanges among nations. We initialize three nations. One nation produces a surplus of oil and the other two have deficits of oil. The oil supplier is subject to perturbations which prevent the consumer nations from obtaining sufficient oil for their needs. One of the consumer nations has the ability to provide security for the supplier for a certain cost. Alternatively, the nation can invest in technology which slowly lowers their dependence on oil. We vary the amount this 'Policy Maker' chooses to invest in technological and/or military measures in a variety of resource distributions.

2 Model Overview

The Exchange Model (ExM) is an agent-based model developed at Sandia National Laboratories that represents interacting nations which exchange resources [2]. Each nation is comprised of sectors and markets. A sector is comprised of a collection of agents (entities) that consume particular resources to produce other unique resources. Each resource a sector produces is consumed by entities belonging to other sectors. Each entity's viability is based directly on consumption of resources and indirectly on production of resources. In this way, a hierarchical co-dependence among interacting entities, sectors, and nations is formed.

We use a metric, 'health,' which is a measurement of an entity's ability to survive. An entity's health has a nominal level that, if maintained, allows continued homeostasis. An entity's health fluctuates based on its ability to consume particular resources at a specific rate. If the entity is not able to consume resources at this specific rate, its health will deteriorate. Alternately, if the entity exceeds this rate of consumption it will become healthier than its nominal level.

Entities exchange resources through markets, which may be international (meaning entities from all nations can use the market to trade resources) or domestic (which prohibits entities from trading unless they are members of the nation in which the market resides). Entities establish an offer and bid price for the resources being traded based on their health, money, and resource levels. Markets allow resources to be matched between entities that consume and produce the same resource using the double auction algorithm.

Perturbations can be introduced into an ExM model simulation to represent resource shortages. Perturbations are imposed on a particular sector within a nation, causing all entities in that sector to lose their store of output resources. This scenario affects both the perturbed entities which now have nothing to sell and the entities who require the lost resource for their own production. The resulting shock ripples throughout the system as entities respond to the disruption.

Some nations are configured with a specialized sector called the government. For the purposes of this model, the government taxes domestic trade, using the money to buy labor. The government uses labor to create a military resource (that buffers perturbations) or a technology resource (that improves the production rate of a resource).

Each national sector consumes the resources of every other sector to produce a single unique resource. In this configuration, the modeled system's network structure is characterized as fully connected with the exception of the government sector which is asymmetric. The effect of network structure on the model's dynamics has been studied by Kuypers et al. [3].

3 Implementing the Experiment

To study the effectiveness of investment in the protection of a critical resource imported from an unstable region versus investment in self-sufficiency, we initialized simulations made up of interactions among three nations; Supplier, Policy Maker, and Drone. Each nation is comprised of five sectors except Policy Maker which has an additional sector called government. The five sectors used here are named to represent relevant commodities: labor, goods, farming, mining, and oil. At the start of every simulation, each nation's production and consumption rates are set for each commodity sector.

The Supplier nation's economy is balanced for all resources except oil. For the labor, goods, farming, and mining sectors production and consumption levels are balanced, the nation produces as much as it consumes. The oil sector produces more oil than the other sectors consume, resulting in a surplus of oil.

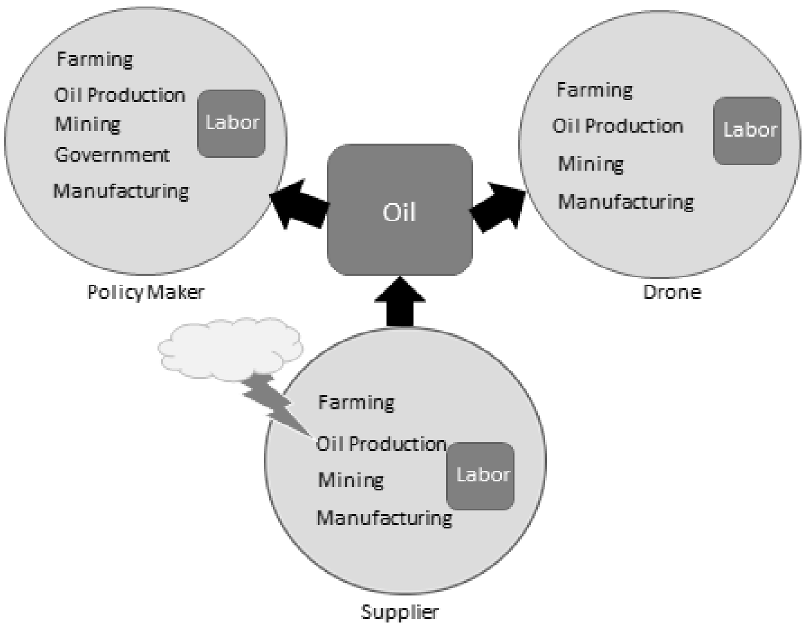

Fig. 1. Diagram of modeled entities (nations and sectors), disrupted production sector and international market for oil showing commodity flow

The Policy Maker's national economy is balanced except for the oil sector as well. However, instead of a surplus, the Policy Maker has an oil deficit. If the Policy Maker cannot trade in the international market to obtain more oil, the health of its sectors falls very low. The Policy Maker's government sector consumes a small fraction of its produced labor resource to produce units of military and/or technology resource. The military can be used to deflect perturbations, the technology can improve domestic oil production.

Similar to the Policy Maker, the Drone nation has a balanced economy except for an oil production deficit and the absence of a government sector to either defend against perturbations or invest in technology.

The Supplier, Policy Maker, and Drone nations have complementary economies. The Supplier has a surplus of oil while the Policy Maker and Drone have a deficit of oil. All resources are traded internationally except for labor.

3.1 Parameter Sweeps

We use a 3-dimensional parameter sweep in which the frequency of perturbations within the Supplier nation, the effectiveness of the Policy Maker's military at buffering those perturbations and the ratio of investment Policy Maker applies towards producing technology versus military are varied to examine the tradeoffs between projecting security and investing in self-sufficiency to buffer resource scarcity.

We investigate four different frequencies at which the Supplier nation is subjected to disruption: low, medium, high, and extremely high.

The effectiveness of the Policy Maker's military is determined using a sigmoid function defined by the following equation:

$$Effectiveness(x) = \frac{x * p}{(1 + p * x^2)} \tag{1}$$

where p is a constant used to scale the function and the variable x describes the amount of military resource the Policy Maker has produced. From the equation we are able to obtain a value for *Effectiveness(x)* which is compared to a randomly generated number between 0.0 and 1.0. If the randomly generated number is less than *Effectiveness(x)* the Policy Maker successfully buffers the perturbation and no resources are lost. If the random number is greater than 1, the perturbation is executed.

Military effectiveness sets an upper bound on the sigmoid function by determining the maximum percentage of perturbations deflected if all Government investment went to military resource production. Setting an upper bound reflects the inherent inability to guarantee the security of supply chains no matter how many resources are invested. Three possible levels of military effectiveness are shown in Table 1.

Also shown in Table 1 are the four possibilities modeled for the third parameter considered, the ratio of investment in technology versus military production.

Table 1. Military effectiveness and tradeoff options. The military effectiveness defines the maximum perturbation deflection probability. The tradeoff data show four ratio options for government investment in military and technology.

Military Effectiveness	Perturbation Deflection Probability
Strong	91%
Average	56%
Weak	20%

Tradeoff	Military Investment	Technology Investment
Option A	60%	40%
Option B	40%	60%
Option C	20%	80%
Option D	0%	100%

We also consider dependence and abundance of oil. Dependency is a measure of oil production rates relative to the total amount of oil production in the system. We vary this parameter over ten different scenarios. Abundance is a measure of the total production and consumption of oil in the system. If there is a global oil surplus then the system has high abundance, while a global deficit of oil means low abundance. For example, a scenario in which global oil production is greater than global oil consumption and, as we have defined for this study, the Supplier nation produces much more oil than either the Policy Maker or Drone nations, a condition of high abundance and high dependence would exist.

4 Results

The multidimensional parameter sweep generates large amounts of data. The results we present here were chosen to highlight the understanding we have gained regarding the general characteristics of the model.

4.1 Low Dependence, High Abundance

First, we consider the case of low dependence and high abundance of oil. The Policy Maker is able to produce enough oil initially to supply its internal demand without importing and thus has a low dependence on the Supplier.

We vary the Policy Maker's investment allocation between technology and military resources and take the average health value of the oil sector of each set of simulations. We find the Supplier's health is highly dependent upon the Policy Maker providing protection from perturbations. The health of the Policy Maker grows as it increases its investment in technology (for more efficient native oil production) over military production (Figure 2).

The price of oil fluctuates widely in each of the 48 individual simulations. The frequency of perturbations to Supplier oil production and the low dependence of the Drone and the Policy Maker results in a weaker demand for oil. When Supplier oil production is perturbed, the other nations are in less need of the oil it supplies, so the Supplier has a harder time recovering. When dependence is high the Supplier recovers from disruption more quickly as the other nations immediately need oil and are willing to pay a premium, resulting in increased money flow to the Supplier.

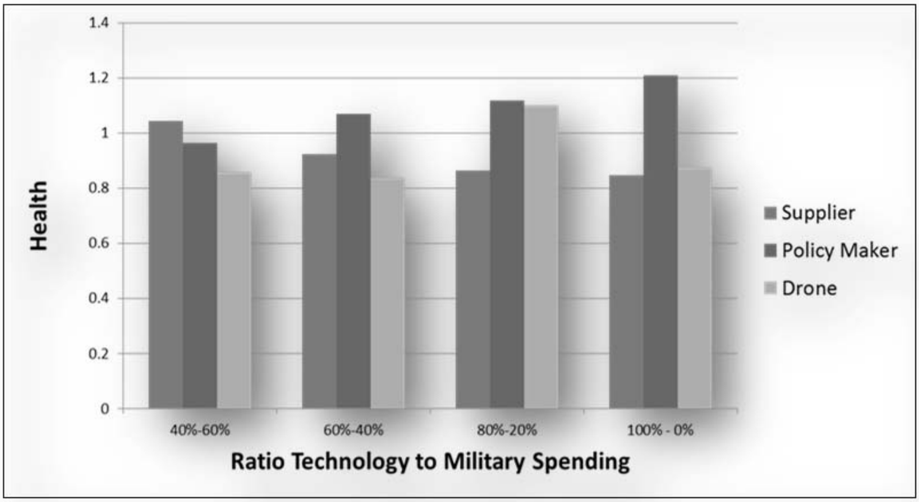

Fig. 2. In a disruption scenario under low dependence and high abundance conditions, the greater the Policy Maker investment in technology, the lower Supplier's health falls and the higher Policy Maker's health rises

4.2 Medium Dependence, Medium Abundance

In the medium dependence and medium abundance disruption scenario, the Policy Maker no longer produces enough oil to supply its demand, thus needing to import oil from the Supplier.

In this case, we find the Supplier's average health is slightly dependent upon the Policy Maker providing protection from perturbations but has a greater than nominal health regardless of the Policy Maker's investment decisions. As seen in Figure 3, since the Policy Maker is dependent on the Supplier for a small fraction of its oil consumption needs, its health increases as it chooses to invest in technology over military production. In this scenario, Policy Maker reaches its nominal health level when the government invests 100% in technology.

Looking at the individual runs, we see a decrease in the magnitude of the price spikes. In this scenario there is a greater dependence on oil from the Supplier requiring the Policy Maker and Drone nations to buy from the Supplier (potentially at a premium), making the consequences of perturbation less devastating to the Supplier.

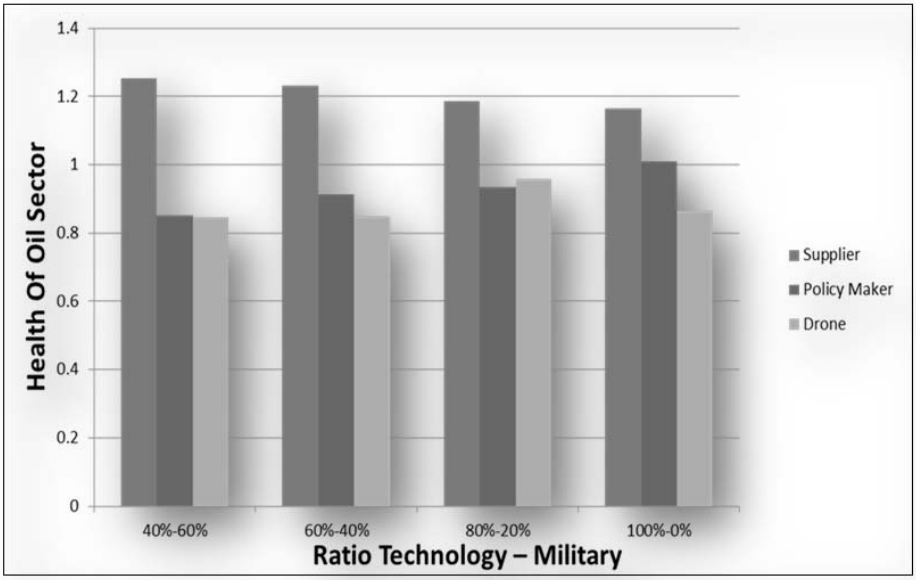

Fig. 3. In a disruption scenario under medium dependence and medium abundance conditions, the Policy Maker's health rises as it invests more in technology. Although this investment policy diminishes the Supplier's health, its level remains above nominal.

4.3 High Dependence, Medium Abundance

When high dependence and medium abundance conditions exist, the model imposes strict constraints on the nations in the simulations. The Policy Maker is highly dependent on importing oil from the Supplier nation to fulfill its consumption demand.

The Supplier's average health is no longer dependent upon Policy Maker protection from the perturbations it experiences. As illustrated in Figure 4, the Supplier also exhibits a greater than nominal health independent of the Policy Maker's investment decisions. The average health of the Policy Maker's oil production sector rises as the nation increases technology investment over military spending up to a 4-to-1 spread. Without Policy Maker providing any protection to the Supplier's oil production sector and despite a 100% investment in technology, all three nations see a decrease in health.

In the individual simulations, the cost of oil can be seen to rise very little. The demand is so great that in all cases, the Supplier is able to withstand the effects of disruptions to its oil production sector.

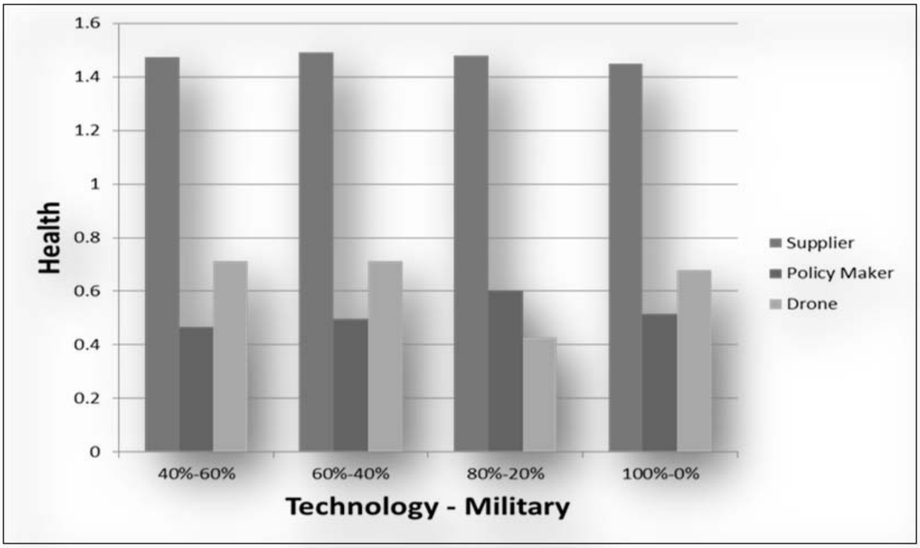

Fig. 4. In the high dependence, medium abundance disruption scenario, the Supplier's health remains very high regardless of the Policy Maker's investment strategy. The health of both the Policy Maker and the Drone fall well below nominal.

4.4 Effects of Dependency

We measure the effect of dependency by taking the difference between the Supplier and the Policy Maker's initial oil production rates and varying them inversely by small increments. In this manner, the world's total production rate of oil never changes, only the dependence of the Policy Maker on foreign oil.

As the Policy Maker's dependence on foreign oil increases, the average health of the Supplier grows. As the Policy Maker becomes more dependent on the Supplier there is less advantage to the health of either the Supplier or the Policy Maker from manipulating military and technology investment strategies. When there is low dependence, different allocation strategies can affect the health levels of each nation's sectors more than under high dependence conditions.

Figure 5 shows the health of the Supplier's oil production sector with respect to the level of the Policy Maker's dependence. Each curve represents a ratio of Policy Maker contributions to technology versus military resources. Figure 6 illustrates the Policy Maker's oil sector health considering the same parameters. To obtain this data from the simulations, we found the average health of the oil sectors having varied military effectiveness, frequency of perturbation and percentage of technology versus military production.

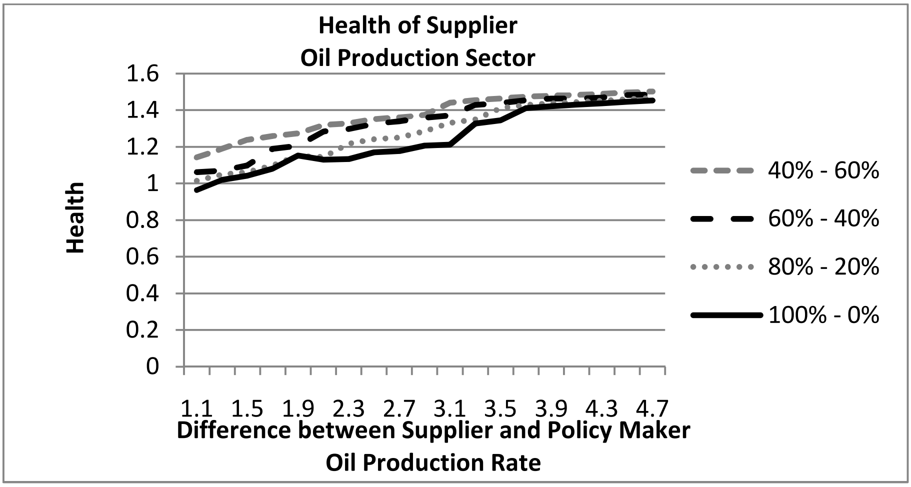

Fig. 5. Health of Supplier's oil production sector. The health values of different allocation strategies converge as the Supplier and Policy Maker's oil production levels diverge.

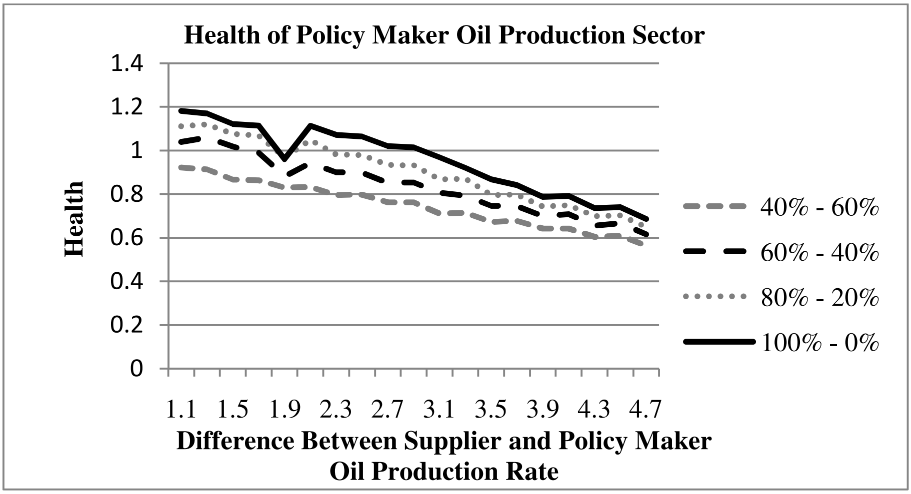

Fig. 6. Health of Policy Maker's oil production sector. The health values associated with different investment ratios converge as the oil production levels diverge.

5 Conclusion

By varying the frequency of perturbations on the Supplier, the Policy Maker's military effectiveness, the oil dependence of the Policy Maker, and global abundance of oil we have been able to comprehensively study the effects of Policy Maker's military and technology resource investment. Counter to our intuition, we found that as dependence on foreign resources increases, national policy has less impact on the health levels of the nation and internal production sectors.

The results of this work can be applied to real world scenarios by asking questions about the state of the world. Is the relevant resource abundant, and how dependent are the nations on each other for this resource? Although this study describes an environment that exists only in simulation, we believe the effects identified through analysis using ExM can be applied to real policies to help policy makers make decisions about situations presenting similar tradeoffs.

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