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A General Model of Resource Production and Exchange in Systems of Interdependent Specialists

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A General Model of Resource Production and Exchange in Systems of Interdependent Specialists

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Abstract

Infrastructures are networks of dynamically interacting systems designed for the flow of information, energy, and materials. Under certain circumstances, disturbances from a targeted attack or natural disasters can cause cascading failures within and between infrastructures that result in significant service losses and long recovery times. Reliable interdependency models that can capture such multi-network cascading do not exist. The research reported here has extended Sandia's infrastructure modeling capabilities by: 1) addressing interdependencies among networks, 2) incorporating adaptive behavioral models into the network models, and 3) providing mechanisms for evaluating vulnerability to targeted attack and unforeseen disruptions. We have applied these capabilities to evaluate the robustness of various systems, and to identify factors that control the scale and duration of disruption. This capability lays the foundation for developing advanced system security solutions that encompass both external shocks and internal dynamics.

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Acronyms, Initialisms, and Abbreviations

CASoS	Complex Adaptive Systems of Systems
DHS	Department of Homeland Security
DOE	Department of Energy
HPC	High Performance Computing
LDRD	Laboratory Directed Research and Development
MS&A	Modeling, Simulation, and Analysis
NISAC	National Infrastructure Simulation and Analysis Center
SNL	Sandia National Laboratories
U.S.	United States

1 INTRODUCTION

The Complex Adaptive Systems of Systems (CASoS) Engineering program at Sandia National Laboratories (SNL) helps inform policies affecting complex adaptive systems of systems. This work is an outgrowth and distillation of several years' experience applying insights from complexity science and complex systems to problems of national and international scope. Many initial problems focused on critical infrastructures such as electric power systems and banking networks [Brown et al. 2004, Glass et al. 2004]. The effects of infrastructure disruptions on economic activity and on other patterns of human interaction are of foremost concern to policy makers. Our experience with diverse technological, economic, and social systems has led us to formulate a simple abstract model that we argue captures processes essential to many complex systems.

Such systems can be described abstractly as a collection of interacting Entities that must meet two requirements for stability: Entities must maintain their individual viability through some homeostatic process involving the consumption of resources obtained from the environment; and the system must foster a pattern of resource flows among Entities to create suitable conditions for their mutual viability.

An abstract model that focuses on these general features is useful for studying the behavior of real systems for at least two reasons. First, it creates a set of terms and parameters that can be used to interrelate systems in very different domains, allowing insights obtained from the study of one system to be reflected onto systems that are superficially dissimilar. Second, a systematic study of the model itself can potentially yield insights about the behavior of many real systems arising from the basic constraints and processes in the model. We define such a model in this paper, and analyze its behavior in example configurations.

2 PROBLEM STATEMENT

Taken as a whole, critical infrastructure is a network of dynamically interacting systems of systems designed for the flow of information, energy, and materials. Under certain circumstances, disturbances from a targeted attack or a natural disaster can cause cascading failures within and between infrastructures that result in significant service losses and long recovery times. Reliable interdependency models that can capture such multi-network cascading do not exist. Individual infrastructures are systems designed to produce and distribute commonly-used resources; many important interdependencies among infrastructures arise from the relationships of resource consumption and production among them. A general understanding of infrastructure interdependencies can be developed through an abstract model of systems composed of specialized resource users.

3 METHODOLOGY

The model comprises a set of Entities, a set of Resources that can be stored, consumed and produced by the Entities, and a set of Markets that mediate resource exchanges among Entities. The connectivity of Entities to markets may reflect the topology of physical networks if such networks are required for resource exchange. The primary state variables and processes that define Entities, including both the internal consumption and production processes and interactions with other Entities through exchange processes, are summarized in the causal loop diagram in **Figure 1**.

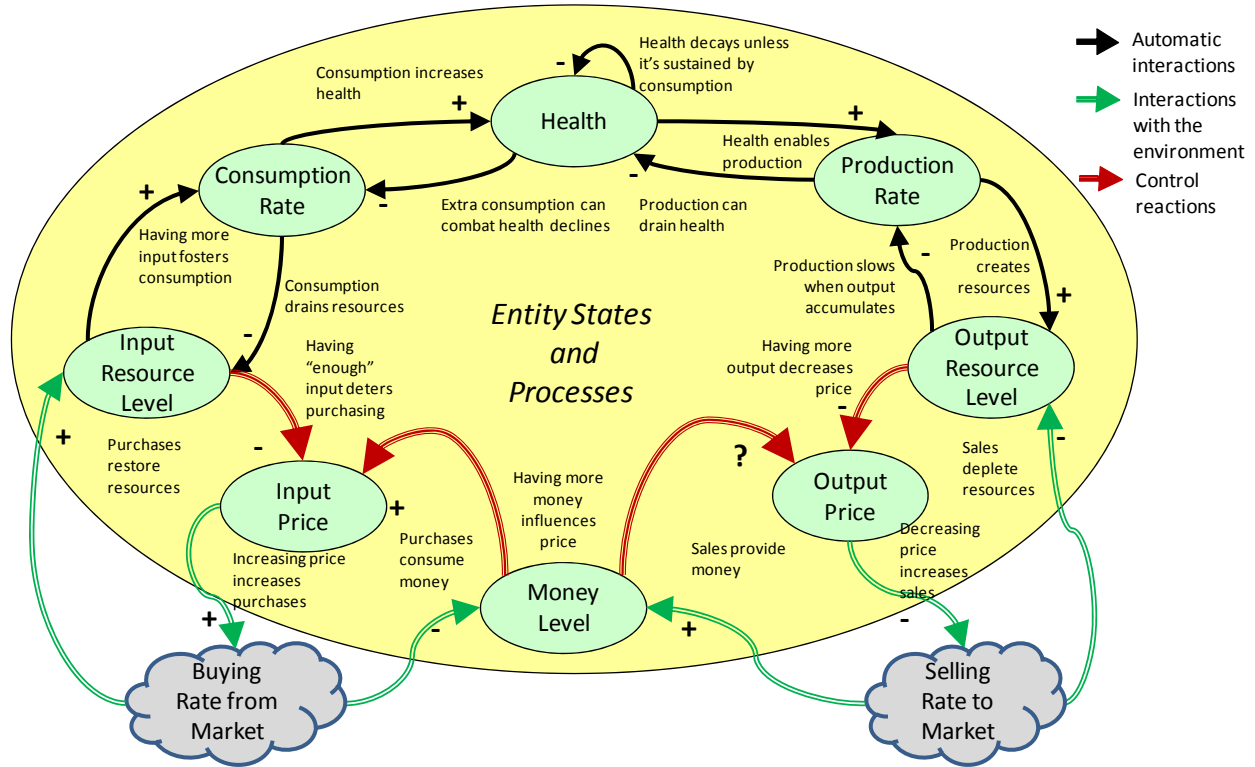


Figure 1: Causal Diagram of the Primary Variables and Interactions Describing an Entity

Entities have some internal structure that accomplishes production and that is maintained by consumption of input resources. The model does not represent this structure explicitly because its details (which vary greatly across systems) are not essential for understanding the system-level behavior arising from interactions among Entities having distinctive resource requirements and production potentials. We use a scalar health variable $h(t)$ as an index of the current state of an Entity's internal structure. The meaning of this abstract variable derives from its influence on production and consumption. Parameters of the functions relating consumption, production, and health can be tailored to reflect the operational characteristics and the specific internal structures that characterize real systems. Entities control their resource levels through interactions with one another via markets. Markets manage resource exchanges among the subset of Entities they serve. Entities send exchange proposals to markets, and markets arrange compatible exchanges among Entity pairs when possible. A common "money" resource is used in all exchanges. The terminology of markets, prices, buying and selling should be understood metaphorically and not as limited to economics and commerce. The "price" an Entity sets for a resource can be

understood as a threshold energy level that the Entity is willing to expend, or commit to extract, in exchange for the resource. The Entity extracts energy from the environment in exchange for the resources it produces, and uses that energy to obtain the resources it needs. Entity behavior is governed by a set of simple control processes and is not assumed to be the result of optimal decision-making or other constructs commonly used in artificial economies [Testafatsion 2006] that might limit application to cognitive agents that are “rational” in the sense of traditional microeconomic analysis.

Entities can submit proposals at any time and may seek to control resource levels by adjusting the size of the proposed transaction, the frequency with which they transact, or some combination of these factors. In practice Entities are configured to make proposals with some specified frequency, and to propose exchange amounts that, together with this frequency, would allow them to either obtain or dispose of resources at a rate much larger than their nominal consumption or production rates. Entities then control the actual rate of transaction by adjusting their prices, as illustrated in **Figure 1**. The logic for setting resource prices is therefore an essential determinant of the Entity’s behavior. Price adjustments are Entities’ primary means of managing interactions with their environment.

Entities with little need to transact signal this by proposing very low prices (as buyers) or very high prices (as sellers), rather than by adjusting their proposal frequencies and amounts. This approach has two important advantages: it greatly increases the amount of information available to the market as compared to withholding proposals, and it concentrates the Entity’s control action on the single parameter of price.

3.1 Process Definition and Stability Analysis

The equations governing the state variables shown in **Figure 1**, along with other details of the model formulation are given in [Beyeler et al. 2011]. The functions that specify each of the causal links in **Figure 1** were designed to have qualitative properties assumed to characterize a broad class of Entities, and to have few parameters each of which have natural interpretations.

An example relevant to configurations studied here is the function defining the effect of health on potential production. This function, $p_{h_i}^*$, is defined so that production can increase, up to some limit, when health exceeds its nominal value h_0 . Production decreases monotonically with health. A sigmoid function fits these criteria.

$$p_{h_i}^* \left(\frac{h}{h_0} \right) = \frac{P_{sat}}{1 + (P_{sat} - 1) \left(\frac{h(t)}{h_0} \right)^{-e_p}} \quad (1)$$

where $P_{sat} > 1$ is the maximum relative production that can be achieved if health becomes large, and e_p is an elasticity parameter that describes how abruptly production changes with health.

The elasticity parameter is derived from the more intuitive parameter $h_{mid_{h_i}}^*$ the relative health level required for a relative production rate of 0.5:

$$e_p = \frac{\ln\left(\frac{p_{sat} - 1}{2p_{sat_i} - 1}\right)}{\ln(h_{mid_{h_i}}^*)} > 0 \quad (2)$$

The existence and stability of the equilibrium solutions for certain simple configurations are determined by the parameters of $P_{h_i}^*$ [Beyeler et al. 2010]. For an Entity that consumes and produces the same single resource, and that has no need to interact with other Entities, its equilibrium condition in terms of normalized health $h^* = h(t)/h_0$ becomes:

$$p_r - h^* = \frac{p_{sat} - 1}{1 + p_{sat}\eta_T} h^{*1-e_p}; \quad p_r \equiv p_{sat} \frac{p_0}{c_0} \frac{1 + \eta_T}{1 + p_{sat}\eta_T} \quad (3)$$

Where p_0 and c_0 are the nominal rates of resource production and consumption, and η_T is a parameter controlling the strength of the burden that production places on health.

Equation (3) cannot be solved in general in closed form, however it can be used to understand the existence and stability of fixed points. **Figure 2** sketches the left and right sides of Equation (3) as functions of normalized health for the range of values that e_p can assume.

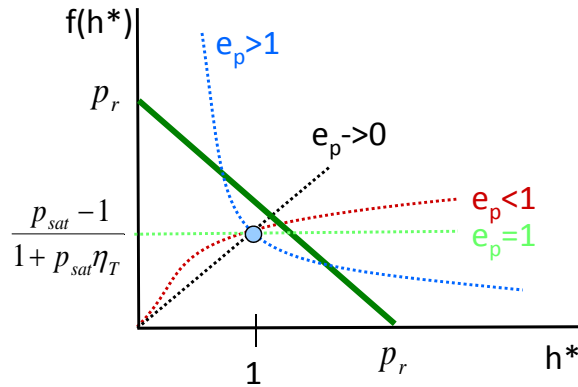


Figure 2: Sketch of stability conditions for an isolated Entity for various ranges of e_p

The system has a stable equilibrium for $e_p < 1$, and for $e_p = 1$ provided $\frac{p_{sat} - 1}{1 + \eta_T} < p_r$. For $e_p > 1$ the system can have no solution (when the blue curve is outside the green line) or two solutions (when it is inside) with a transition between these regimes. In the case of two solutions only the lower equilibrium is stable: states between the two equilibria are driven to the upper solution, and states below cause the Entity's health to collapse.

The stability analysis has interesting implications for an Entity's response to certain kinds of disruption. A loss of production capacity (equivalently episodic random losses of the produced resource) corresponds to a reduction in p_0 and therefore p_r , shifting the green line toward the origin. When $e_p < 1$, the Entity will be able to find a stable but reduced health value. When

$e_p > 1$ however, the Entity is liable to undergo catastrophic collapse as the reduced production narrows and ultimately eliminates the attractor basin for stable solutions. Larger values of e_p result from smaller values for the surplus production capacity P_{sat} or larger values for the health required to maintain production h_{mid} . Both changes represent a more “efficient” production process in the sense of being tuned to the Entity’s nominal operating point and having little ability to respond to stresses by either increasing production or continuing production in the event of degraded health. The third example configuration, discussed below in Section 3.3, uses this interpretation of P_{hi}^* to show how competitive pressures for efficiency might tend to push Entities to the edge of stability.

3.2 Exchanges and Markets

Entities exchange resources with one another via proposals to buy or sell resources. They communicate these proposals to Markets which match buyers and sellers when their proposals are compatible. Each Market manages exchanges of one specific resource. The system can include many markets for the same resource (perhaps serving different Entities) and Entities can transact in multiple markets for the same resource.

Although many matching algorithms might be used to accomplish these transactions, we currently use the continuous double auction because of its simplicity and potential to settle exchanges immediately. The Market is not intended to mimic the operations of a specific exchange process, even in applications where economic transactions are conducted, but to perform the essential function of conveying information about the relative scarcity of resources.

Proposals to markets are defined by the role of the Entity (either buyer or seller), the amount of the proposed transaction, the proposed transaction price, and the length of time for which the proposal is valid. When a proposal is matched by the market, resource amounts and money are exchanged between the matched Entities. Markets may impose a levy on the money or resource involved in the exchange.

The exchange resulting from a matched proposal can exhibit different patterns over time, and the extension of the exchange over time influences the way Entities price their proposals to exchange (see **Figure 3**).

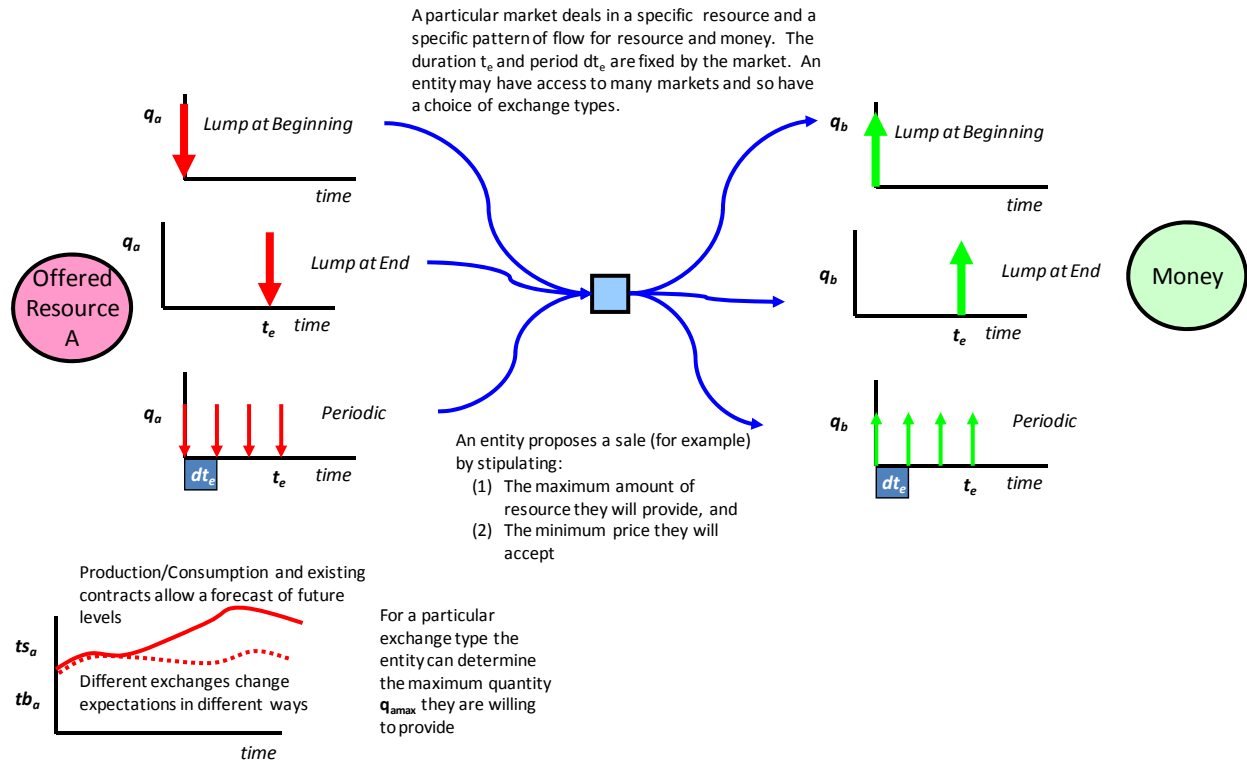


Figure 3: Possible Patterns of Resource and Money Flow that Constitute an Exchange between Entities

Figure Note: Lump transfers at the time proposals are matched correspond to spot exchanges; all other patterns of exchange are contracts of some kind.

The simplest pattern is a spot exchange, in which resources and money are transferred at the time the proposals are matched. Contractual exchanges are distributed over time in a way determined by the form of the contract. Contracts can be interpreted as interdependency links between Entities which form and expire over time, creating a dynamical network structure.

4 IMPLEMENTATION

The model has been implemented as a library of Java classes. The implementing code is divided into three groups of packages (organized as related Teamforge projects) with distinct roles. The ExchangeJ project (<https://teamforge.sandia.gov/svn/repos/phoenix/models/ExchangeJ>) contains code artifacts that correspond to model features (such as Entities and Resources). This project contains core code required by all applications.

The ExchangeViewer project (<https://teamforge.sandia.gov/svn/repos/phoenix/models/ExchangeViewer>) contains the mechanisms for running a particular configuration of the model. Two execution modes are provided. The first (using the ModelRunner class) is intended for unsupervised (batch) execution, either locally or on a High Performance Computing (HPC) resource. It creates one or more configurations of the model by iterating through an archive of specification parameters, such as a flat file or database table. This is the primary mode of model execution for uncertainty analysis. The second execution mode (using the ModelViewer class) is intended for interactive construction and execution of the model, typically during initial development. Network views allow users to navigate the model structure and interrogate the state of Entities during model execution.

Specific systems or problems require specific configurations of the model, i.e. definition of Resources, types of Entities, types and connectivity of Markets, and so on. Both the basic model classes in ExchangeJ and the execution environments in the ExchangeViewer project are designed to be independent of the specific features of a model application. The execution environments are made independent through their use of a ModelFactory interface. Implementations create models that are tailored to specific systems or problems. The ExchangeVizDriver project (<https://teamforge.sandia.gov/svn/repos/phoenix/models/ExchangeVizDriver>) contains the set of implementations (currently 17) used to explore and apply the model. **Figure 4** shows the basic design elements used to create application-independent execution environments for both batch and interactive use.

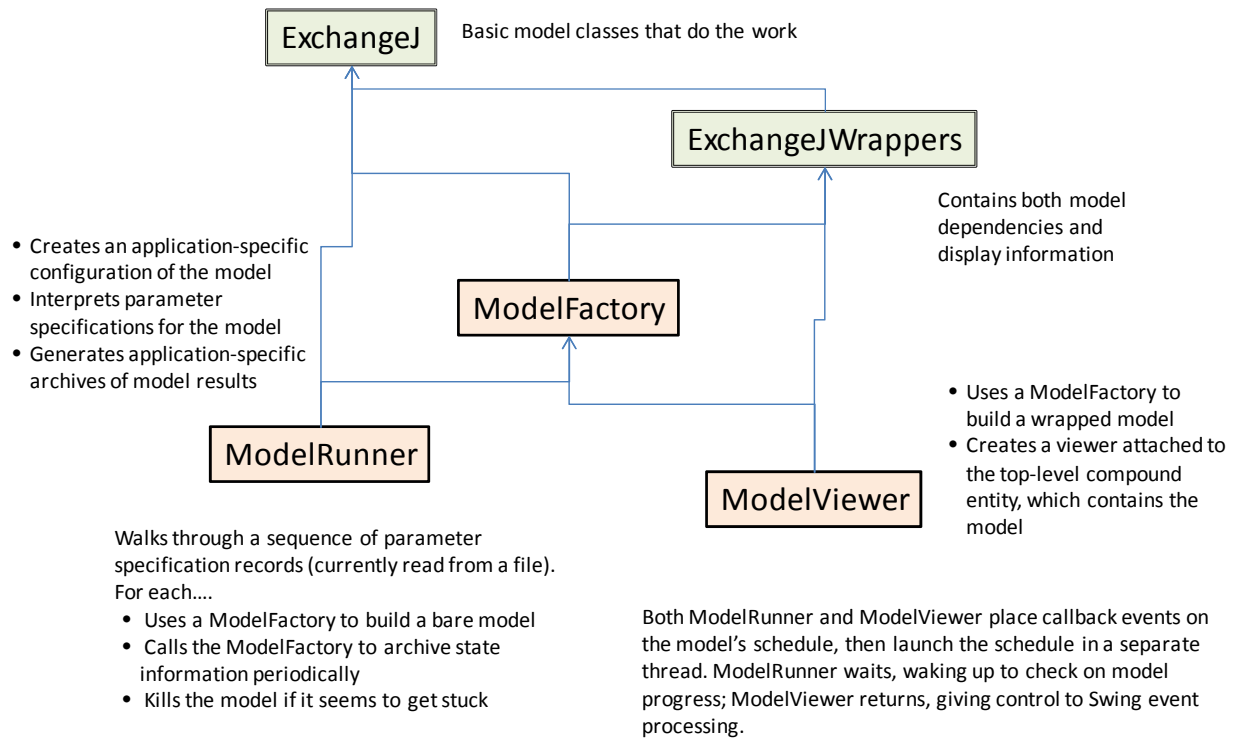


Figure 4: Fundamental Interfaces (orange) and Packages (green) used to Create Application-Independent Execution Environments Suitable for both Interactive Model Analysis and Remote Parallel Evaluation for Uncertainty Quantification

5 APPLICATIONS

We've used the model to study the behavior of a wide variety of systems; five of these applications are the subject of forthcoming publications and are summarized here. The first was designed as part of a study of simple patterns of resource interdependencies that Entities might have. Exploration of parameter sensitivities led to a surprising result of competitive exclusion. This study has been expanded (Mitchell et al., forthcoming) to investigate the relative advantages of different growth strategies in environments with episodic changes in resource availability. The second application considers two economic regions with different production characteristics in their component sectors. The effect of introducing inter-regional trade in selected resources on the flows of resources within these regions is explored. This work is being extended (Kuypers et al. forthcoming) to understand the fundamental stability characteristics inherent in element sectoral structures. The third application considers how environmental perturbations influence the outcome of competition among Entities that must trade off productive efficiency and tolerance of shocks, illustrating the potential for highly optimized tolerance [Carlson and Doyle 1999] to develop in systems of this kind. This analysis has been extended (Norton et al., forthcoming) to shifts in population composition associated with scarcity-driven transitions from one dominant strategy to another. The fourth application begins an examination of the behavior of networks of specialized producers and consumers, such as characterize industrial economies (Beyeler et al., forthcoming). The final application summarized here uses the structure and resource flows in an agricultural supply network to build a probabilistic model for utilizing observations of food contamination in retail outlets to identify possible sources of contamination. This application was part of a food defense strategy developed for the Department of Homeland Security (DHS) through the National Infrastructure Simulation and Analysis Center (NISAC) program (Conrad et al., 2011).

5.1 Competitive Exclusion

This configuration was designed as part of a study of basic interaction patterns among Entities rather than as a model of a real system. It contains four resources, arbitrarily labeled A, B, C, and D. Each Entity in the system consumes two of the resources and produces both of the resources it does not consume. As defined in **Table 1**, there are six basic Entity types corresponding to the unique partitionings of the four resources into unordered pairs.

Table 1: Definition of the Six Entity Types by their Input and Output Resources

Entity Type	Resources Consumed	Resources Produced
CDMaker	A,B	C,D
BDMaker	A,C	B,D
BCMaker	A,D	B,C
ADMaker	B,C	A,D
ACMaker	B,D	A,C
ABMaker	C,D	A,B

The system is closed, and has redundancy at two levels. Each Entity can substitute between its inputs to some degree and can shift production between its outputs. At the system level, each resource is produced by three Entity types and is used by three types (**Figure 5**). This redundancy confers some resiliency against disruptions to individual Entities and to the availability of individual resources.

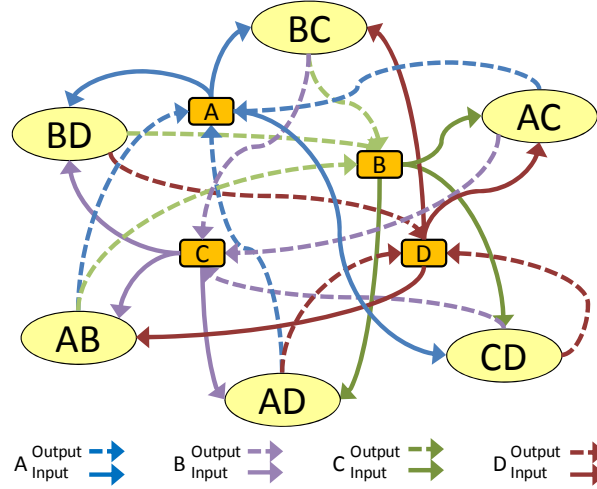


Figure 5. Diagram of Markets and Competing Producers of 4 Resources

We used the model to explore the consequences of one Entity type dominating production of a particular resource or resources. We first created a general condition of scarcity by setting the baseline consumption rate for all resources to 2 with a baseline production rate of 1. We then increased the CDMaker's baseline production rate parameter p_0 for both of its output resources to 5 from its nominal value of 1. Our naïve expectation was that the Entity having increased potential production would use this potential to increase its health at the expense of other Entities. The result, shown in **Figure 6**, was surprising but easy to understand in retrospect.

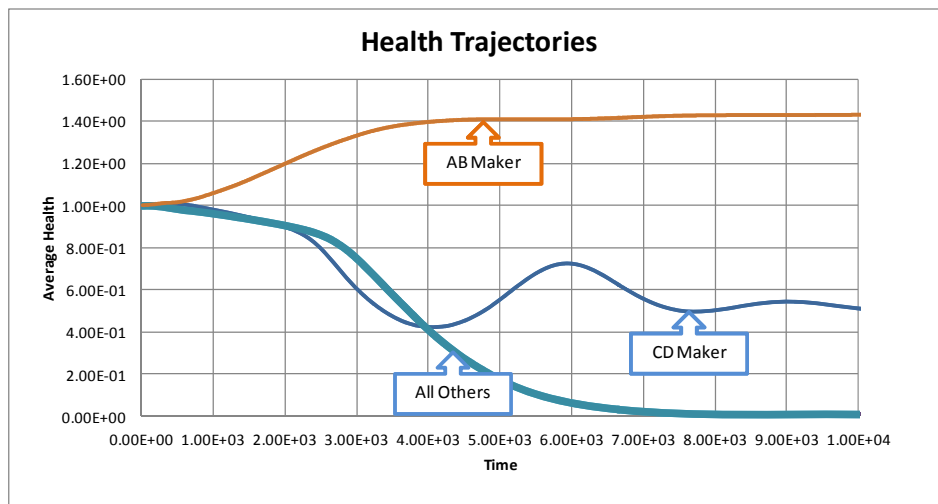


Figure 6: Average Health Values for each Entity Type when Nominal Production Rate of CDMakers is Increased

The Entity type that benefits from the enhanced production capacity of CDMakers is not CDMakers but ABMakers because they consume both of the relatively abundant resources (C and D) and produce both of the relatively scarce resources (A and B). Other Entity types consume one of the scarce resources and produce one of the abundant resources, but their production efficiency is lower than that of CDMakers. These Entity types are unable to capture enough money (or energy) from production to obtain the input they require and are therefore driven to extinction. The elimination of competing producers allows CDMakers to “negotiate” terms of exchange that are somewhat more favorable, allowing a slight increase in health between times 4000 and 10000.

The exploitation of some advantage (here surplus production capacity) to eliminate competitors would not be surprising if the Entity’s decision-making included a strategic picture of their environment, but the Entity has no model of the environment. It is simply adjusting price levels (or energy thresholds) in response to changes in internal resource levels. This particular behavior is also of interest because the initial redundancies with which the system was endowed have been eliminated, resulting in a final configuration consisting of two mutually interlocked types. Whether or not episodic shocks to the system would divert this trajectory and preserve a richer mixture of types is a question for further study.

5.2 Effects of Inter-Regional Trade

This application considers two economic regions. Each is represented by a Compound Entity.. Each region has six component Entity types representing sectors of the regional economy: households, mining, manufacturing, water provision, agriculture, and energy production. These sectors exchange six kinds of resource: Labor, Food, Water, Energy, Raw Materials, and Goods. Each is produced by a specific sector using inputs from other sectors.

The two regions differ in the relative efficiency with which resources can be produced.

Table 2 lists the nominal input and output coefficients for each sector-Entity type in the two regions. In Region 1 the processes tend to consume more energy and less labor than in Region 2, and household consumption of all resources is larger in Region 1 than Region 2.

Table 2: Nominal Input and Output Rates for Economic Sector Entities

5.3 Region 1 – More Energy Intensive, Higher Consumption by Households								
	<i>Consumption Rate for Each Resource</i>						<i>Produced Resource and Rate</i>	
<i>Sector Entity Type</i>	<i>Labor</i>	<i>Food</i>	<i>Water</i>	<i>Energy</i>	<i>Raw Materials</i>	<i>Goods</i>	<i>Production Rate</i>	<i>Resource</i>
Household		3	3	3		3	0.8	Labor
Mining	0.1		0.5	0.5			1	Raw Materials
Farming	0.1		3	1			4	Food
Water Supply	0.1			0.5			8	Water
Manufacturing	0.4			3	1		3	Goods
Energy Production	0.1		0.5				8	Energy
Total	0.8	3	7	8	1	3		

Region 2 – More Labor Intensive, Less Consumption by Households								
	<i>Consumption Rate for Each Resource</i>						<i>Produced Resource and Rate</i>	
<i>Sector</i>	<i>Labor</i>	<i>Food</i>	<i>Water</i>	<i>Energy</i>	<i>Raw Materials</i>	<i>Goods</i>	<i>Production Rate</i>	<i>Resource</i>
Household		1	1	1		0.5	1.2	Labor
Mining	0.2		0.5	0.2			1	Raw Materials
Farming	0.5		3	0.3			1	Food
Water Supply	0.2			0.2			7	Water
Manufacturing	0.5			1	1		0.7	Goods
Energy Production	0.1		0.5				2.7	Energy
Total	1.5	1	5	2.7	1	0.5		

In each of the two regions, we create three instances of each economic sector using the input and output coefficients in

Table 2. Each region includes one market for each of the six resources, which connects all producers and consumers of the resource within the region. The nominal resource flow rates through these markets would be roughly three times the totals in

Table 2 if each Entity's demands could be feasibly satisfied. We first consider the resource flow rates and sector health levels in the two regions without interregional communication. **Figure 7** illustrates the health trajectories in the two regions; resource flow rates are listed in the first column of **Table 3**. Based on their nominal input and output rates from **Table 2**, the Farming and Water Supply sectors in Region 1 have production capacities somewhat in excess of the total nominal demand from the other sectors. The health of these sectors is therefore somewhat depressed relative to the health of other sectors, as the left half of **Figure 7** shows. Mining and manufacturing are similarly depressed in Region 2 owing to their spare capacity.

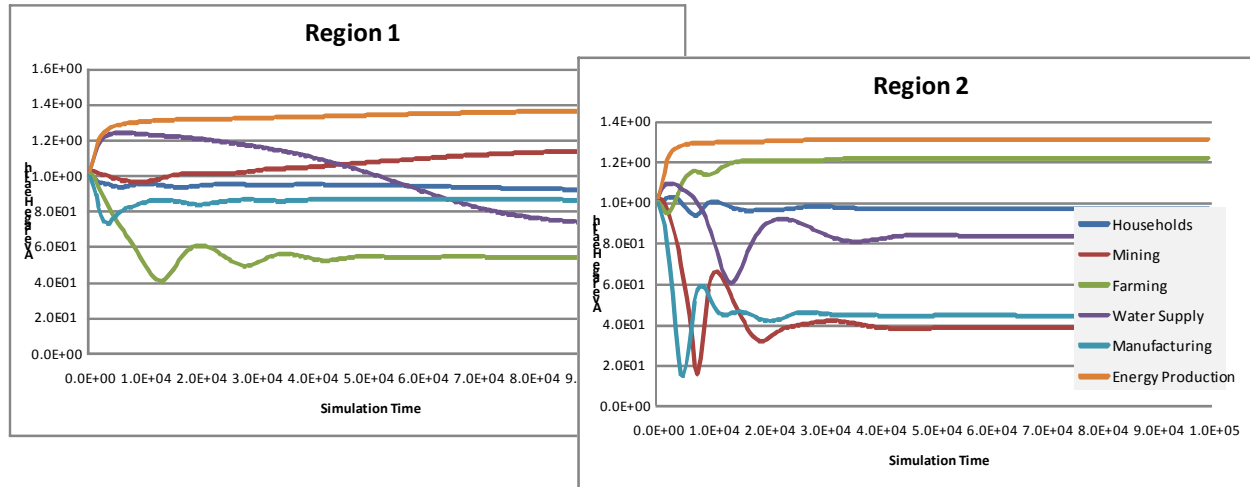


Figure 7: Average Health Values for Each Sector without Inter-regional Exchange

Table 3: Total Resource Flow Rates through Regional and Inter-Regional Markets for Three Cases of Inter-Regional Connection

Resource	Inter-Regional Markets							
	None		Goods			Goods and Raw Materials		
	Region 1	Region 2	Region 1	Region 2	Inter Regional	Region 1	Region 2	Inter Regional
Labor	2.03	3.14	2.04	2.69		1.91	3.14	
Food	8.53	2.70	8.28	2.50		8.96	2.71	
Water	18.45	17.25	17.89	16.78		19.02	18.11	
Energy	21.32	7.24	21.48	6.11		20.50	6.41	
Raw Materials	2.60	1.89	2.65	0.00		0.00	0.00	2.18
Goods	7.48	1.43	6.56	0.00	1.07	4.80	0.00	2.42

We next add an inter-regional market for Goods, which enables Households in both regions to buy Goods from Manufacturers in either region. No tariffs or transportation costs were imposed on inter-regional exchange (although the model allows them). **Figure 8** shows the trajectories of health, and the resource flow rates are given in the central columns of **Table 3**. The

manufacturing sector in Region 2 is extinguished, and because there is no other consumer of Raw Materials the Mining sector collapses as well. All goods are now produced in Region 1, and although the total flow of Goods from Region 1 is somewhat larger than in the case of no inter-regional exchange (6.56+1.07 vs. 7.48) this total flow is *smaller* than in the case of no inter-regional exchange. Region 1 shows a slight increase in labor use, while Region 2 sees a comparatively large decline. This decline in labor underlies the decline in total goods consumed.

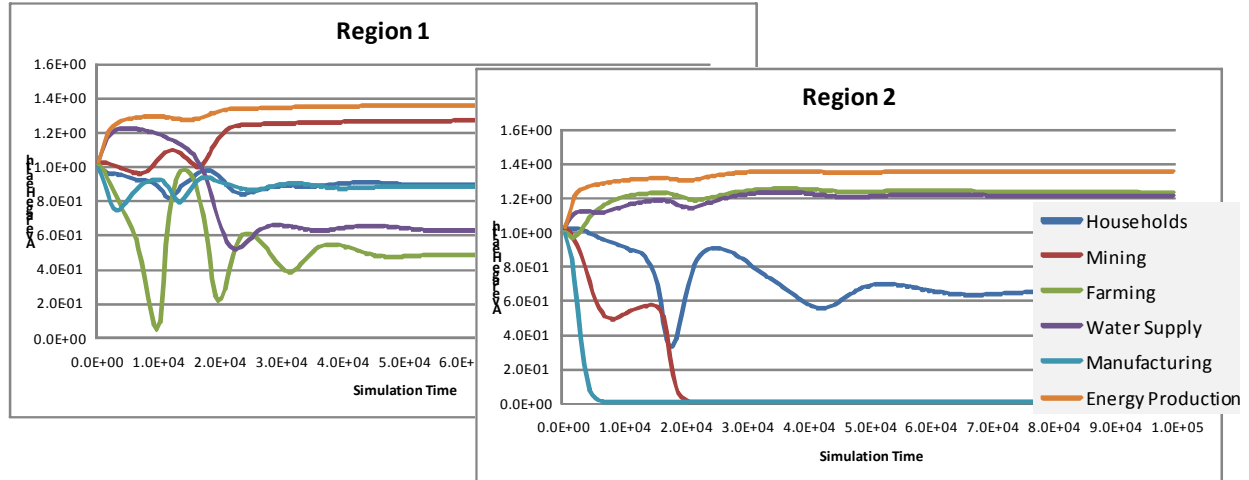


Figure 8: Average Health Values for Each Sector with Inter-regional Exchange of Goods

Finally, we include an inter-regional market for Raw Materials as well as Goods. **Figure 9** shows the trajectories of health in the two Regions: the last columns of **Table 3** list resource flow rates at the end of the simulation period.

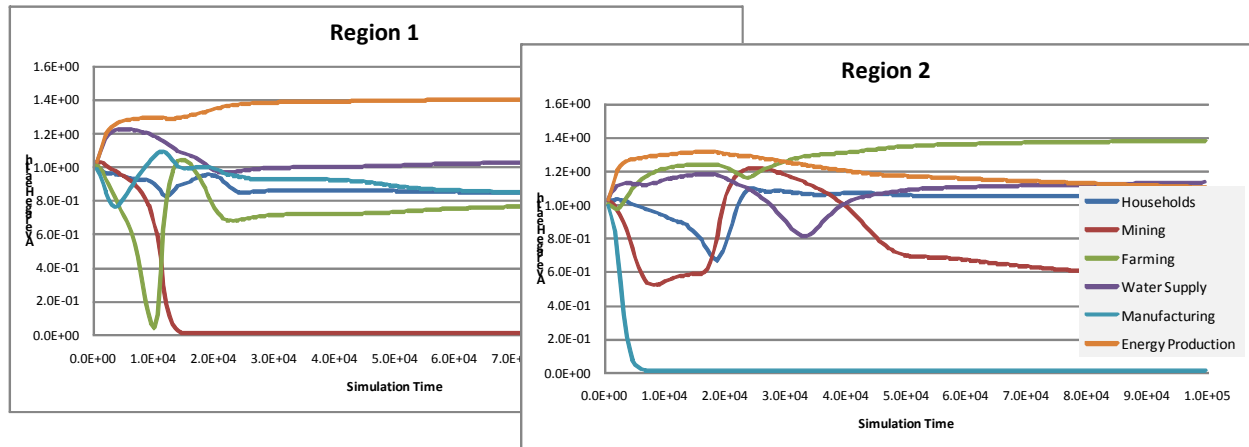


Figure 9: Average Health Values for Each Sector with Inter-regional Exchange of Goods and Raw Materials

Here we see a different pattern of specialization in which all Raw Materials are being produced in Region 2 and sold to the Region 1 Manufacturing sector, which is still the exclusive producer of Goods for both regions. The total production rate of Goods is again lower than in the case without inter-regional exchange, and the flow of Raw Materials is substantially lower. This is

last reduction is largely due to the diversion of Raw Materials into the more-efficient Manufacturing sector in Region 1.

The definitions of economic sectors, and the coefficients used to describe them, were arbitrarily chosen for illustration. Models composed of hierarchical Entities managing populations of specialized producers can clearly give insights about possible consequences of international trade patterns; this configuration is a start toward such applications.

5.4 Balancing Robustness and Efficiency under Disruption

In the first two applications, the system adapts through changes in the operating state of the component Entities in response to their interactions. Adaptation can also change the *composition* of a population of interacting Entities through selection. The third configuration uses the model to study how trade-offs between Entities' efficiency and stability are shaped by the environment to which they become adapted.

The stability analysis discussed in Section 1 helps pose the problem. There we see that parameter values of the function $p_{h_i}^*$ (Equation 1) which lead to greater stability correspond to functions that maintain production as health is diminished and that enhance production if health becomes elevated (**Figure 10**). These features suggest that the production process, however it is implemented by the Entity, has some redundancy and surplus capacity that is lacking in Entities characterized by steeper and shorter $p_{h_i}^*$ functions. Maintaining this redundancy and surplus is presumably more costly than maintaining a less robust process in that it requires the consumption of more input resources. We therefore use the parameters of $p_{h_i}^*$, as **Figure 10** shows, to define a cost factor for the Entity, which is used to adjust its nominal consumption rate.

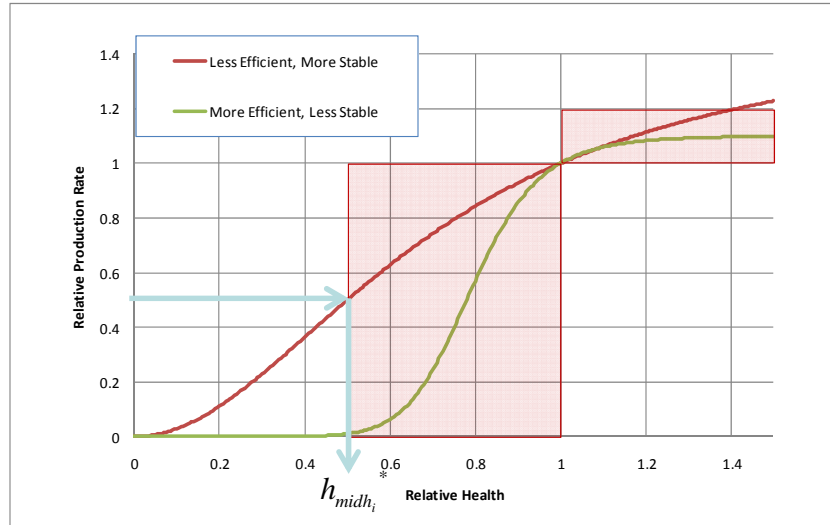


Figure 10: Production/Health Functions Corresponding to Different Efficiency/Robustness Choices Indicating the Cost Associated with Robustness

Intuitively the area outside the maximally efficient production function (a step function at $h^*=1$) represents robustness that requires the support of additional consumption. If an Entity's baseline

consumption rate is c_{b0} , its nominal consumption rate is increased to reflect the cost of robustness:

$$c_0 = c_{b0} \left[\left(1 - h_{midh_i}^* \right) + \frac{1}{2} \left(\frac{p_{sat}}{1 + (p_{sat} - 1)2^{-e_p}} - 1 \right) \right]^\alpha \quad (4)$$

where the added terms approximate the areas under the production/health function that represent additional robustness in the production process. The first approximates the area under the curve for health less than 1, and the second the area above a relative production rate of 1 for health values between 1 and 2. α is a parameter that can be used to adjust the weight given to robustness costs.

We use a simple mutualistic design to study the influence of an adaptive environment on the trade-offs Entities make between more stable, more costly production functions (a “robust” configuration) and less stable, less costly (“efficient”) functions. There are two Entity types: one produces resource X by consuming resource Y, and the second produces Y by consuming X. There are 100 instances of each Entity type, and each population is maintained by replacing an Entities that die with new instances. Y-producers all have identical parameters, while X-producers each have different production functions defined by random samples of the defining parameters $h_{midh_i}^*$ and p_{sat} reflecting differing “choices” regarding cost and stability. X-producers and Y-producers interact through markets. These interactions are one component of the Entities’ environment. Exogenous shocks are a second component. Individual X-producers can be subjected to random removal of some fraction of their current inventory of resource Y.

Differences in parameter values among X-producers can lead to different health trajectories, including death. The populations of X-producers, and Y-producers if necessary, are periodically refreshed by replacing dead Entities with new instances. This process allows us to see the selective effect of the environment on the composition of the population as ill-suited parameter combinations tend to be filtered out. Replacement by sampling the population of survivors in some way, rather than reverting to the initial distributions, would add the second half of an evolutionary dynamic, however focusing on the filtering characteristics of the environment can give important initial insights before adding new instabilities and complications to the model.

Environmental stresses are specified by two parameters: the ratio of the total nominal production rate of Y in the system to the total nominal consumption rate (the Y abundance), and the presence or absence of random shocks to the X producers. In addition, the common production parameters $h_{midh_i}^*$ and p_{sat} for the Y producers were varied from simulation to simulation.

We anticipated that increasing stress on the X producers, by decreasing abundance of the Y resource, would encourage efficiency in the X producers and filter out the less efficient, more robust producers (those with smaller e_p values) from the final population. Introducing random shocks to the system by episodically removing Y resource from randomly-chosen X producers was expected to favor X producers that incur the cost of robustness and filter out the more efficient (larger e_p) X producers. These expectations were substantially borne out by the results.

Figure 11 shows the average value of e_p over the final population of 100 X producers for 500

sampled values of Y abundance and the two Y production parameters $h_{midh_i}^*$ and p_{sat} , with and without exogenous disruptions.

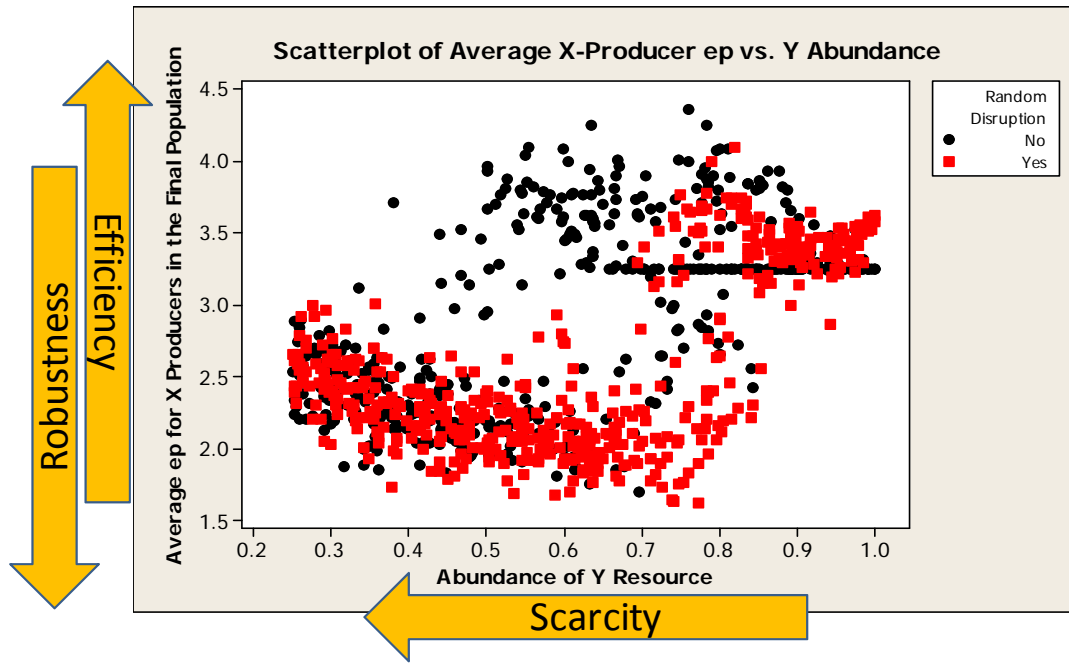


Figure 11: Average e_p in the Final Population of X Producers vs. the Relative Abundance of Y in the System

There is a general trend toward more efficient X producers (larger average e_p values) as the Y resource becomes less abundant, but this trend is seen in two distinct clusters of results: one consisting of relatively efficient producers at moderate to high levels of abundance and a second of relatively robust producers at low to moderate levels of abundance. The system response can be understood by first considering the cases with high abundance (above 0.65) and no disruption (black dots). In many cases, all Entities in the initial population of X producers survive until the end of the simulation, so that the population average of $e_p \approx 3.25$ is unchanged from its value over the initial set of samples. These cases create the line of results extending down to an abundance of approximately 0.65. In other cases some X producers do expire and are replaced, allowing some selection on the basis of e_p . For high abundance levels above 0.9 adding exogenous disruption can evidently foster *efficiency* by pushing marginal Entities into extinction. As abundance declines from 0.7 to 0.5, the system develops distinct stable states: one with relatively high e_p values (also having relatively large resource flows and health), and the second with low e_p values (and roughly half the resource flows). In an environment with no disruption the system can often occupy the “higher” state and Entities can continue to compete on efficiency; adding disruption in this range invariably filters for more robust configurations by eliminating Entities with larger e_p from the population. For the cluster of runs at lower e_p values, there is effectively no distinction between disrupted and undisrupted runs. This implies

that the random removal of input inventory from individual X producers is a small stress relative to the general shortage of Y in the system.

5.5 Stability of Production Networks

Modern economies involve large numbers of specialized production processes generally coordinated through markets. Viewed as a network of resource flows and transformations, we would like to understand the factors that control the response of this system to disruption. This understanding can't come from an analysis of the current structure of the economy, even if that structure could be defined, because that structure is only a single observation in the space of economic relationships which we would like to characterize. To explore this space we define a process for constructing realizations of production networks, and study the behavior of many realizations of this generative process.

The generative process proceeds from a small number of basic assumptions about the purpose of, and constraints on, production networks. First, we assume that there is an overall directionality to resource flows, beginning with primitive resources that require no inputs for their production ("raw materials"), flowing through various stages of transforming processes, and ending with resources that are consumed for their own sake ("consumer goods"). Second, we assume that there are no circular flows in the network.

The system comprises instances of Entity types, which interact to produce a directed flow of resources of various kinds. Each Entity type uses a specific set of resources as inputs, and produces a specific set of resources as outputs. A particular resource might be produced by more than one Entity type. Entity types can be divided into layers based on their structural distance from the producers of primitive resources, which are by definition in the first layer. Entities that only use resources produced in the first layer as inputs are defined to be in the second layer. In general the layer number of an entity is one more than the largest layer number of the entities that produce its inputs. The network as a whole is defined by describing the Entity types in successive layers, as detailed below. Any number of layers may be specified.

Each resource in the model is traded through one or more markets. For describing the participation of Entities in markets (when multiple markets exist) it is convenient to use Entities' locations. Basing market participation on an Entity property, rather than on random connection of Entities to markets, can create correlations in supply conditions across resource types and across Entity instances. Such correlations may have an important influence on the system's propensity to propagate disruptions. For this purpose a one-dimensional world is adequate: each Entity instance is assigned a location from $[0,1]$. The world is wrapped to avoid edge effects, so that $L=0$ corresponds to $L=1$. These locations are randomly assigned to Entity instances when they are created. A particular type of Entity might be geographically concentrated. This feature is described by the location of the center of concentration of Entity locations, and the degree of concentration of Entity locations, for each type of Entity. Because the types are randomly generated these parameters of the location distribution are themselves sampled from a range of values that define the layer.

Each layer produces a distinctive set of resource types. A given resource type might be produced by only one type of Entity in the layer, or might be produced by several types of Entity. Each layer definition includes a probability distribution for the number of producer types for

resources. Input resources for the Entities in a layer can come from any prior layer. The probability distribution of the source layer of input resources describes this feature. Resource types produced in a layer may not be equally “useful” in the sense of being used as inputs to some subsequent process. The dispersion of resource use in a layer describes the variability in usage probability across resources types produced in the layer.

Each resource is traded through one or more markets, which are associated with the layer in which the resource is produced. Each market is associated with a range of locations. The interval $[0,1]$ is uniformly divided among the markets. A market is connected to all resource producers and customers whose locations fall in its range. In addition, producers and customers may have connections to some other market, regardless of location. The supplier dispersion specifies the probability that a resource producer has such a connection, and the customer dispersion is the analogous probability for a consumer.

The set of markets in a layer are described by probability distributions, over the resources produced in that layer, of the number of markets for the resource and the supplier dispersion and customer dispersion. The distribution for the number of markets is specified explicitly. Dispersions are stipulated as beta distributions, and described by mean and standard deviation.

The system description consists of a series of layer definitions. Any number can be provided, and all layer descriptions have the same structure (**Table 4**):

Table 4: Parameters Describing a Layer in the Stochastic Production Network Model

Parameter	Description
NT	Number of Entity types in the layer
NinMin, NinMax	Minimum and maximum number of input resources for a type
NoutMin, NoutMax	Minimum and maximum number of output resources for a type
NinstMin, NinstMax	Minimum and maximum number of instances for each type
Xcmin, Xcmax	Minimum and maximum locations for the center of concentration of instances
Dlmin, Dlmax	Minimum and maximum values for the dispersal of instance locations
Pin[k]	Probability that an input resource derives from the k'th preceding layer
Pprod[n]	Probability that an output is produced by n types
DRU	Dispersion in the probability that a resource type produced in the layer is used in a subsequent layer. 0 => only one resource type is ever used, 1 => each type has an equal probability of being used
DmsdMean, DmsdStd	Mean and standard deviation of the beta distribution for supplier dispersion across resource markets in the layer. DmsdStd=0 produces a constant dispersion for all markets
DmcdMean, DmcdStd	Mean and standard deviation of the beta distribution for customer dispersion across resource markets in the layer. DmcdStd=0 produces a constant dispersion for all markets. DmcdMean < 0 causes the customer dispersion for a market to

	be the same as the supplier dispersion.
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One difficulty with the probabilistic description of network structure is that individual realizations may have anomalous features that make them unrepresentative of real economic systems. Generated networks must therefore be filtered and preconditioned to make them suitable for subsequent analysis.

A resource produced in one layer might not have been selected as an input resource in any subsequent layer. Such resources are productive dead ends, and are removed from the model. Removing these resources may leave an Entity type with no product resources. Any such Entity types are also removed, along with their dependence on input resources. Removing this dependence may leave these resources with no consumptive use, precipitating another round of elimination. Following this pruning, all resources in the production network will be inputs to one or more Entity types, and all Entity types (other than the final consumption layer) will produce one or more resources for use by other Entities.

Resources with no consumptive use in the network, and Entity types which produce no resources, are eliminated because the economic dynamics of real production systems will not tolerate such features. Economic processes presumably tune production networks in other ways, matching Entities' production capacity and resource markets. The appropriate size for a given Entity, which determines its nominal consumption and production rates, depends both on the overall structure of the system and on the sizes of its potential suppliers and customers. Rather than determining the set of Entity sizes through an initial optimization of some kind, we define a new growth dynamic that causes Entities to adjust their size based on the health level that their environment allows them to achieve. The size S of an Entity evolves by the following state equation:

$$\frac{dS}{dt} = S * \frac{\left(\frac{h(t)}{h_0}\right)}{tGrowth} \quad (5)$$

Where $\frac{h(t)}{h_0}$ is a normalized value of health, and $tGrowth$ is a time constant which governs the rate at which an Entity can change its size. Entities that can initially spend less for their inputs than they can make from their outputs will have elevated health levels, and will increase in size. Entities in the complementary condition will shrink. This process is self-limiting since growing Entities will increase demand for their inputs and supply of their outputs, and shrinking Entities will decrease input demand and output supply. The size of Entities in the final "consumer" layer is fixed, which anchors the growth process for the system as a whole.

This framework creates a high-dimensional space of production network structures, and exploring this space exhaustively is not the central purpose of our research. We have begun this exploration to verify the applicability of the exchange model to this class of problems, and to understand how the degree of specialization in a production network might influence its stability. We have examined a set of systems with seven layers, each having approximately 15 Entities, and systematically varied the number of Entity types in each layer from 1 to 8.

Table 5 summarizes the configurations.

Table 5: Configurations used to study stability/diversity tradeoff

Number of Entity Types per Layer	Number of Instances of Each Type
1	15
2	8
3	5
4	4
5	3
6	3
7	2
8	2
9	2
Common features <ul style="list-style-type: none">- Each Type produces two Resources- Seven layers- Each resource has a 50% probability of being produced by one kind of Entity and a 50% chance of being produced by 2 kinds- Each resource has a 50% probability of trading in a single market and a 50% probability of trading in two regional markets	

For each configuration, 20 realizations of the production network were created and simulated. Each system simulation lasted until the growth dynamic had stabilized or the system had collapsed through failure to find a stable pattern of Entity sizes. Instability in the growth process can be understood as a mismatch between the time for an Entity to change its size and the time for information regarding overall resource demand and scarcity to be diffused through the production network. That this diffusion time can depend on the structural diversity of the network can be seen in **Figure 12**, which shows an example network having one Entity type per layer and another example having nine Entity types per layer.

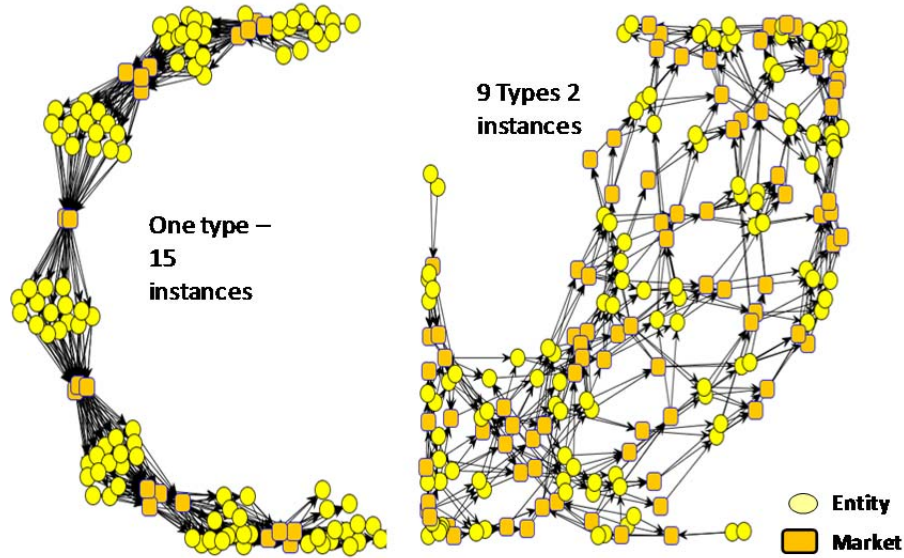


Figure 12: Example Realizations of Production Networks with Low Diversity (left side) and High Diversity (right side)

Figure 13 shows the results of the stabilization time analysis by plotting the time to stabilization, for those systems that did reach a stable configuration (red dots) or, for those systems that did not stabilize, the time at which the last Entity died (black dots), as a function of the number of Entity types in each layer.

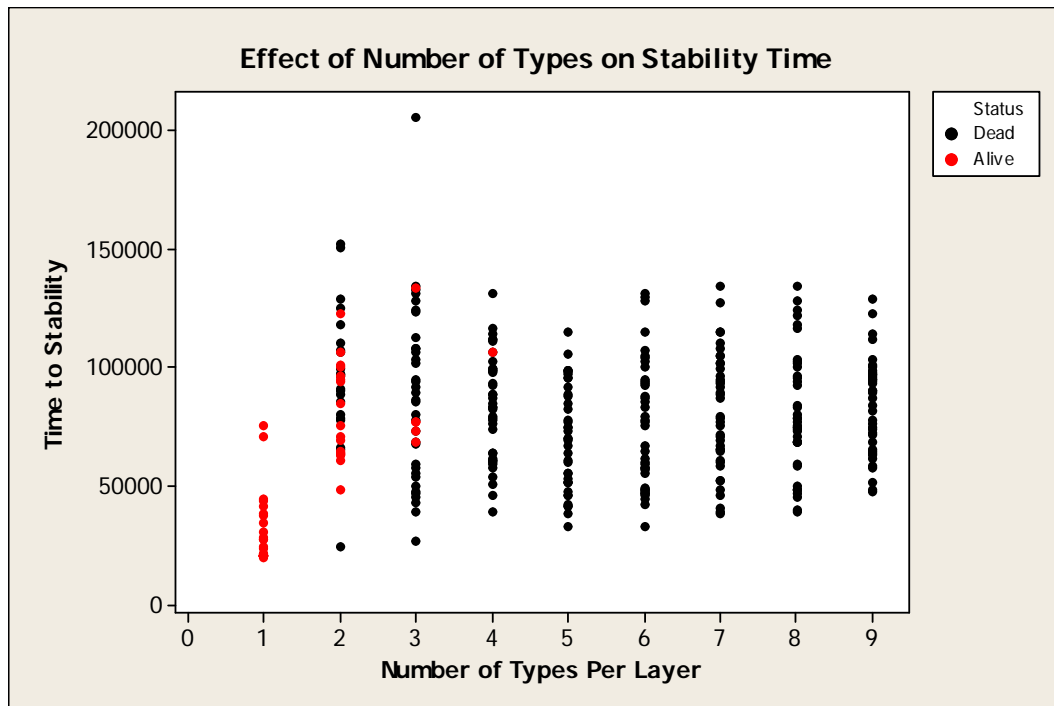


Figure 13: Time for Production Networks to Stabilize (red dots) or Die (black dots) as a Function of Network Diversity

More complex networks are clearly less likely to stabilize than simpler networks. The most varied network having a stable realization contained only four Entity types in each layer, and only a single realization from this set reached a stable state. There is an apparent increase in stabilization time as the number of Entity types increases from one to two in each layer; however the persistence of this to more varied networks cannot be assessed due to the small number of stabilized networks.

5.6 Contaminant Flow through Agricultural Networks

This configuration was developed to support a risk mitigation strategy for protecting consumers from an attack on the food distribution system (Conrad et al., 2011). The goals of this strategy are to reduce the likelihood of significant contamination events by understanding where best to control and monitor flows through the food production system, and to expedite identification of contaminant sources in the event of consumer exposure. Modeling flows of agricultural resources is therefore an important component of this strategy.

Information about the movement of agricultural products will never be complete, even if historical information is perfect. Changes in the industry, such as changes in business practice or response to market dynamics, will change the pattern of flows in the future. The parts of the system involving markets are inherently stochastic. The Resource Exchange model is well suited to study the possible movements of produce both in the current system and the possible flows under changed conditions. The basic processes represented in the model (Figure 1) were supplemented to simulate the movement of contamination, introduced at any point in the system. This capability helps identify locations or processes that might create unexpected vulnerabilities; simulate the effects of mitigation measures that might be used to prevent contaminant spread; and look for patterns in contaminant spread that could help pinpoint the source based on detection events downstream.

Model Entities represent individual businesses of various kinds (farms, processors, distributors) and Markets organize the movement of goods from one Entity to another. Markets can represent actual locations where products are exchanged but more often model a set of buyer/seller relationships that form over time (due to proximity, historical experience, and mutual business or social contacts). Products can move from any seller to any buyer in a market, depending on their rules for managing inventory and on their current circumstances.

5.6.1 Discrete Entity Processes

The basic Exchange Model dynamics for entities are continuous; however, crop and food production is a discrete event process. Crops are sold to processors in lots of some size. Buyers generally process or repackage the produce in some way, but transactions usually involve a shipment consisting of transfers of units of some standard quantity. We use discrete events consisting of discrete quantities of goods to model this process. The focus of this model is on whether or not each discrete shipment (e.g., seed lot, truckload of produce, case of produce) is contaminated or not.

In addition to the Resource production and management processes represented in **Figure 14**, we are interested in how processing can transfer contamination from inputs to outputs (physical

dispersion) and how information about input sources can get lost during processing. These are related but distinct problems. Resource storage can be important because it can cause mixing, information loss, delays in propagation, and growth opportunities for biological contaminants.

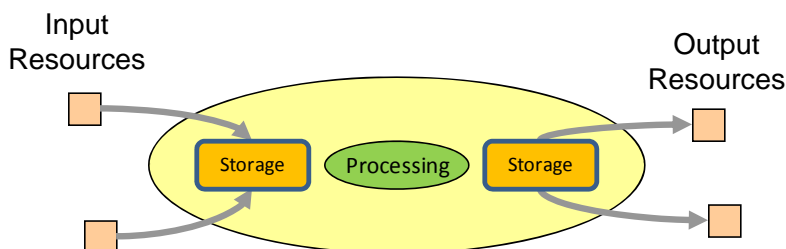


Figure 14: Generic Processing Entity

Each process operates on batches of a specific size, which require a certain amount of resources of each type used in the process. Input resources are physically mixed within each batch and contaminated inputs result in contaminated outputs. This mixing may cause contamination to spread because of processing. The size of the output batch for a process relative to the size of the input shipments will influence the ability to trace back to the origin of contamination (**Figure 15**).

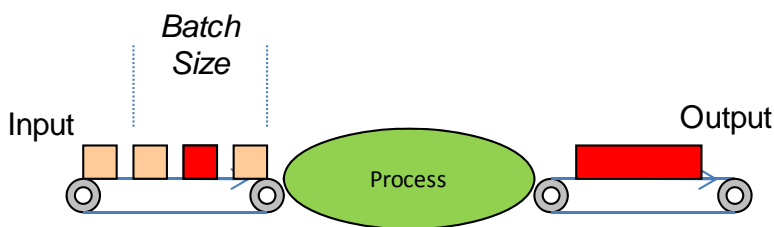
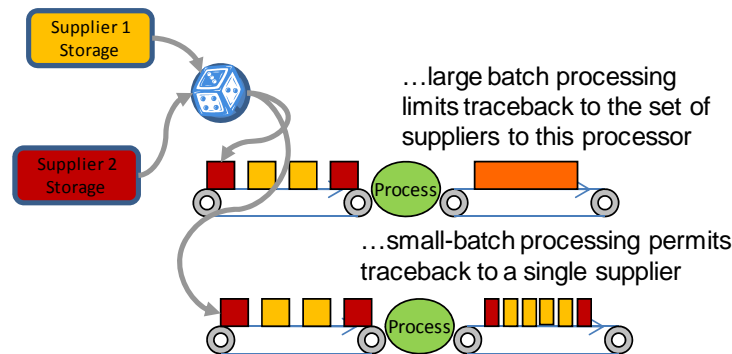


Figure 15: Batch Processing Creates Discrete Output Quantities from Discrete Input Quantities

Inputs from distinct suppliers are selected according to an operational rule. Two idealized cases cover the range of possibilities with respect to preservation or loss of supplier trace-back capability (**Figure 16**). Random selection models either physical mixing of inputs from different suppliers or lack of record-keeping on supply. Systematic selection, drawing from suppliers in order, models either deliberate supply segregation or JIT processing of large shipments. Systematic selection preserves full trace-back capability.

Random selection models either physical mixing of inputs from different suppliers or lack of record-keeping on supply. *It may overestimate dilution by neglecting clustering of contaminated inputs in bins.*



Systematic selection draws from suppliers in order. It models either deliberate supply segregation or JIT processing of large shipments

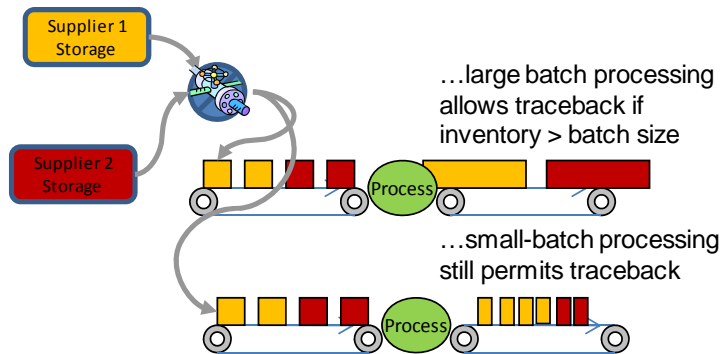


Figure 16: Output Shipments Selection Process and Batch Size Influence Contaminant Spread and Traceback Capability

5.6.2 Example Results

Figure 17 shows the results of a simulation of the spread of contamination through the production network for edible sprouts in New Mexico. This system was chosen to demonstrate the strategy due to its relatively small size and the relatively easy access to data. The model includes seed brokers (open circles), sprout growers (open triangles), sprout distributors (open squares), and retailers and restaurants (filled triangles). In the example shown in Figure 17, 1000 units of contaminated seeds are sold to the Roswell Seed Company which in turn sells them to Keen Ridge. The resulting sprouts are sold both to customers who buy directly from Keen Ridge, and to diverse retail customers (primarily Miscellaneous Restaurants) through Labatts and Shamrock distribution companies. Because individual retailers only use a few clam-shells of sprouts daily (from 2 to 20) large contamination events are likely to affect many retailers. Small events may produce contamination at a single retail outlet.

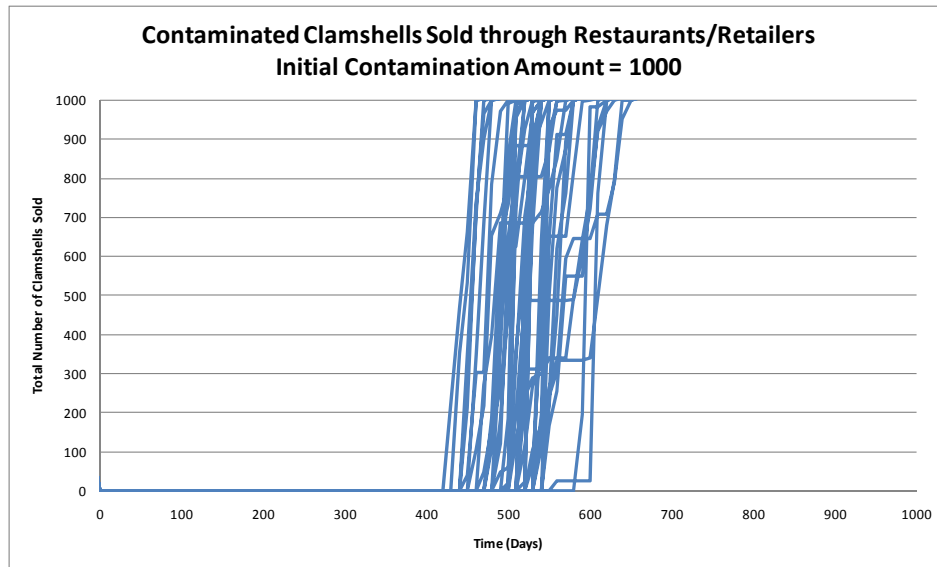


Figure 18: Total Retail Sales of Contaminated Spouts over Time for a FIFO Inventory Management Policy for 50 Runs

By contrast, **Figure 19** shows the cumulative volume of contaminated sprouts sold through retailers assuming *random* seed inventory management. In the simulations, contaminated sprouts are sold as early as 110 days following introduction of contaminated seed, and the last observed sale occurs 1710 days after contamination. For comparison the time interval for contaminant sales in the FIFO case is shaded in orange. Random inventory management is much more diffusive and leads to much greater variability in arrival times across the set of simulations.

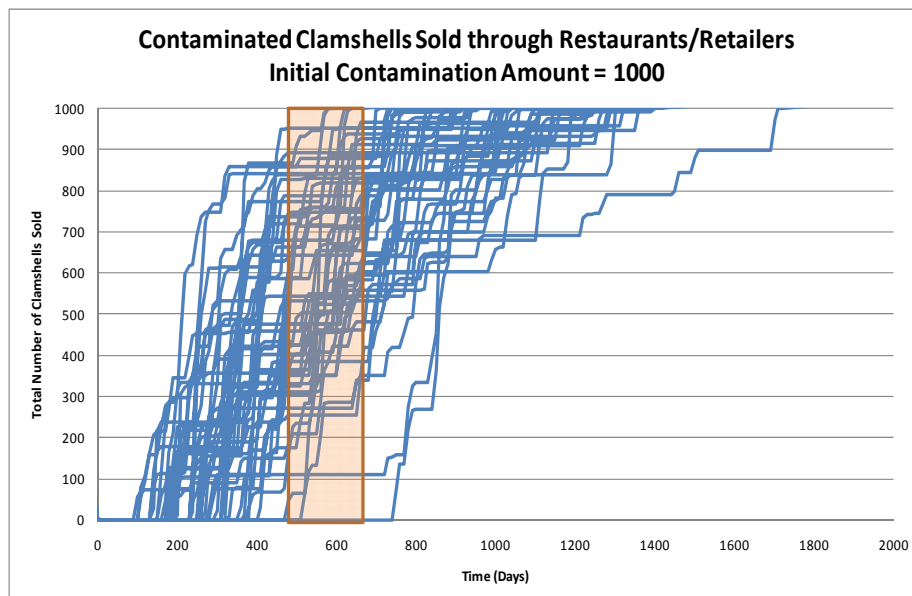


Figure 19: Total Retail Sales of Contaminated Sprouts over Time for Random Seed Inventory Management Policy for 50 Runs (FIFO results fell within the range marked in orange)

This particular application did not focus on the dynamics of resource flow and production, but used an equilibrium pattern of resource flows as a mechanism for moving and spreading contamination. The results demonstrated how the Exchange model can be customized to include domain-specific process features, such as batch processing and inventory tracking and management, when those features are important for solving the problem. The application also demonstrates how uncertainty analysis can be used to identify system features (inventory management practices in this case) that strongly control system behavior.

6 SUMMARY OF RESULTS

We have developed and applied a general model for the interaction of large numbers of individual Entities whose properties and dynamics are suited to the analysis of infrastructure systems, but are not limited to those systems. Entities consume and produce Resources, with different Entity types having different patterns of resource use and production. Resource exchanges among Entities create interdependencies. The scope of these exchange patterns and the Resource management practices of the Entities shape the scale and duration of disruptions to the state of the system precipitated by localized failure.

We have used a Java-based implementation of this model to study the behavior of several disparate systems. These studies have demonstrated the flexibility of the model, but have also revealed unexpected system behavior, such as competitive exclusion and abrupt transitions in strategic viability with increasing resource scarcity. The results and surprises produced in these initial applications so far seem particular to the modeled systems. For example the observation that a diversity of Entity types in a production network leads to a greater chance of instability depends on constraints we've placed on the analysis, such as preserving the total number of Entities and adopting a simple generative mechanism for production networks. This observation is not likely to generalize to all systems covered by the model. Some general features are suggested, for example the propensity for differences in production capacity to lead to extinction in some contexts, as was seen in both the competitive exclusion application and the inter-regional trade application. That there are no obvious universal behaviors across the applications we've examined should not be surprising. These applications were largely chosen to verify the model's applicability to many different systems: they were selected to be highly dissimilar and (excepting the study of contaminant flow through agricultural networks) only explored to the point of yielding preliminary insights.

Two of the example applications described in this report might be easily expanded to address important problems confronted by Sandia customers. . First, the simple model used to look at inter-regional trade effects has obvious application to problems in international economic relations, including energy production and trade, and to international relations more generally. The global production and consumption of essential commodities and natural resources can be used to induce trade flows among nations or collections of nations. The ability of different nations to sustain essential resources flows over time can be studied, as well as the effectiveness of alternative policies in fostering growth and stability. This class of applications would be of interest to Sandia's traditional customers as well as other agencies such as the State Department. Second, the preliminary model of production network stability was developed as an initial step in modeling the robustness and failure characteristics of real industrial production systems. Insights from such modeling can be a great help to the various interests and institutions exposed to risks from these systems. Some infrastructures of specific interest to the Department of Homeland Security, such as industrial chemical production and food supply, can be analyzed to understand the possible scope and duration of problems caused by natural or intentional disruption. The structure of a particular industry, such as aircraft manufacturing, formed by the pattern of resource flows within and among firms will strongly influence the performance statistics of its components. Losses in some areas may be amplified in others, and may lead to compensating profits in other areas. These kinds of linkages can be easily derived from an appropriately

configured model, and would be of obvious interest to any financial firms or insurance companies that have stakes in the industry's performance.

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