Multiple Modeling Approaches and Insights for Critical Infrastructure Protection

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Abstract. Infrastructures provide the foundation for national economic vitality, security and every day comforts. The systems, processes, facilities and experts that form these infrastructures are sophisticated, complex and highly interdependent. Over time, these physical, human and cyber components have evolved toward economical and efficient systems that are robust against random failures and natural events. This evolution creates greater interconnectedness and complexity. Modeling is an essential process for anticipating and understanding how these complex, interdependent systems will respond to disruptions and changing conditions. Natural disasters, malevolent attacks, changes in regulations or market policy all have the potential to disrupt the flow of infrastructure goods and services. No single model or modeling approach is sufficient for answering the breadth of near-term and long-term questions being asked relative to critical infrastructure protection at a local to international level. This article presents the results of six years of model development at the National Infrastructure Simulation and Analysis Center (NISAC), USA; including the types of models developed, their utility in answering critical infrastructure protection questions and general insights regarding infrastructure behaviors and propagating effects of disruptions.

Key Words. Infrastructure interdependencies, infrastructure modeling, NISAC, complex adaptive systems, system dynamics, network optimization, agent-based modeling, micro-economics

Introduction

Infrastructures exist in an environment that subjects the components to natural hazards and accidental damage. They are built to withstand everyday disruptions and, with ingenuity, modified and repaired so that the services they provide can be restored quickly to the people that rely on them. Modeling is a tool that can aid in understanding these complex systems, how they function under normal, stressed and altered conditions and the effects of other systems on their operations. Infrastructure operators use models to evaluate their systems under normal conditions and to design changes or additions to those systems. Using models to evaluate infrastructures under disrupted conditions is not generally needed for system operations. Understanding the effects of potential disruptions on a national level or even local level is beyond the control and responsibility of an infrastructure or system owner or operator. In the United States, federal agencies such as the Departments of Homeland Security, Energy and Transportation are responsible for the protection and regulation of the industries that form the nation's infrastructures. These agencies have to understand the normal operations, threats, vulnerabilities and potential consequences of disruptions; in order to identify and prioritize protective measures, prepare for and assist in the response to natural disasters and unexpected disruptive events and to make risk-informed policies and regulations.

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The effects of disruptions can play out quickly and over long time frames. We are often aware of the immediate impacts such as a regional power outage and associated spoiling of food, shortages or potential contamination of drinking water, and business closings. Longer term impacts are more difficult to trace back to the event. Models are useful in evaluating both types of effects. Models of immediate and near-term impacts help us prepare and improve our responses to disruptions and to identify ways to prevent or reduce the consequences. Analysis of the longer-term impacts (months to years) in a system or infrastructure, provide a way to evaluate policies and system changes that are proposed to fix a near-term problem but have the potential to cause gradual changes that negatively impact the system.

The variation in the types of events that could occur, the range of locations, magnitude, and timing, relative to the environmental and social conditions that might exist, create a very broad scope of analyses that need to be performed. Those analyses must account for the complexity of the infrastructures, their interdependencies and potential system and human responses. No single model is sufficient to answer all the questions for even one infrastructure [1]. This paper provides an overview of the types of models that have been developed for the National Infrastructure Simulation and Analysis Center (NISAC) and a few examples of their utility.

1. Model Development Approach

If we start with a working definition of networks as a collection of entities (nodes) and the relationships between those entities (links), having a specific structure that can change over time (evolve), then networks can be a complex set of relationships between people (social networks), things (physical networks) or both. In the broadest sense of the term (physical and social), network theory forms the basis for all modeling and analysis done within NISAC. NISAC network based models include: network flow models (electric power, telecommunications, natural gas, air transportation, road transportation and rail transportation systems), system dynamics models that have both human and physical components and processes (telecommunications, natural gas, petroleum and water transportation), agent based models of social and physical networks (e.g., micro-economic models) and combinations of these models (coupled network models).

The network flow models range from urban to national in spatial scale and hours to weeks in the timescale simulated. NISAC system models ranging from detailed operations models of a single system within an infrastructure (e.g., port operations) to aggregate models of infrastructures and interconnected infrastructures at a regional to national level (e.g., petroleum and natural gas). The simulation periods for the existing dynamic system models range from days to years.

The diagram in Figure 1 lists the priorities for infrastructure modeling and their characteristics that lead us to use different, and in some cases multiple modeling approaches.

Highly Connected & Interdependent Infrastructures	**Essential and Highly Dependent Infrastructures**	**Economic Sectors**	**Assets**
Energy Banking & Finance Telecommunications Transportation	Health Care Ag & Food Water Government Chemical	Residential Commercial Industrial	
Commerce and national economic security depend on these infrastructures	Human health and safety depend on these infrastructures	Source of demand and labor for infrastructures	Network elements and potential targets

Figure 1. NISAC model and analysis tool development strategy based on infrastructure and sector characteristics

Because of their interconnections, dynamics and interdependencies, energy, banking and finance, telecommunications and transportation infrastructures are evaluated, described, analyzed, and modeled in a variety of ways. When we are evaluating changes in physical capacity due to the loss of one or more assets within a single infrastructure, network models are used. Energy is simulated as single (e.g., electric power) and multiple, interacting networks (e.g., electric power and natural gas). Network models are used to simulate physical systems using constitutive laws that govern the physical flows. System dynamics models are used to evaluate potential system behavior under altered or disrupted conditions and the ability to meet demand over time given system constraints such as: initial storage volumes; storage, production and transportation capacities; priorities for delivery of services; and information about system conditions. The system models simulate aggregate behavior (e.g., change in demand or price at a regional level). Agent-based models are used to simulate the effects of individual behavior and relationships (e.g., contractual arrangements) on system response to altered conditions and to identify the differential impacts that may occur (e.g., operational status of small businesses vs. large businesses by location) as a result of a disruption or policy change.

Another way to classify models is by how realistic or abstract they are. Realism builds confidence that a model is a close representation of the system being simulated, that the basis for the representation is data from the actual system and it captures or re-creates the same outcomes as the system would experience under the same conditions. Realism allows calibration and comparisons to experimental or historical conditions. It also adds complexity to the model that makes gaining insights more difficult and it may or may not accurately represent the system under conditions that have not been measured or observed. Simpler, more abstract models provide a means for evaluating uncertainties about the system or conditions that may lead to greater vulnerability or consequences in the event of a disruption or un-expected event and are easier to understand and evaluate. The comparison of simple (more abstract) model results to those of a more complex or more detailed model (more realistic) may help build confidence in the simple model and better understanding of the more realistic model. The diagram in Figure 2 lays out the range of models developed for NISAC from realistic to abstract.

Realistic → Abstract

Decreasing detail, computation and development time

Data on system elements – for a limited set of conditions	High-fidelity models of individual infrastructure elements	System models of aggregate supply and demand conditions	Generic, highly abstracted network models
Event Library **Commodity Flow Surveys** **Industry Data** **Regulatory Data** **Census Data**	**N-SMART (telecom)** **R-NAS (rail)** **ATOM (air)** **IEISS (energy)** **UIS (urban suite)** **N-ABLE (microeconomics)**	**Port Operations** **Petroleum System** **Natural Gas**	**Loki toolkit (complex adaptive networks)**

Figure 2. Characteristics of the tools used for analyzing infrastructures with NISAC examples

Network analysis yields a new, complementary way of thinking about infrastructure-related systems of systems. We are in the early stages of applying these models and analyzing infrastructure risks and mitigation measures. The next two sections provide examples of how these models have been used and the types of insights they are providing. We begin with the simple and highly-abstracted models of the Loki toolkit and end with the highly detailed microeconomic models in N-ABLE.

2. Adaptive and Dynamic System Models

Infrastructures are dynamic, complex, adaptive systems. System dynamics models are useful for evaluating the aggregate behavior of a system; helping us find tipping points in the dynamic behavior from normal to less than normal operational capacity, from stable to unstable operational conditions and from economically competitive to failing. Aggregation simplifies the representation of the system and makes it easier to evaluate and understand the impacts at a larger scale. Complex, adaptive systems models allow us to represent the network abstractly (as a network topology with statistical characteristics that are representative of the actual network) and evaluate the effects of that topology on system robustness to different types of failures and attacks.

2.1. Complex Adaptive System and Network Theory Based Models

NISAC's Loki Toolkit is a set of components that can be selected, specialized, and combined to create models of diverse networks including power systems, pipelines, social networks, and financial networks, as well as interactions across these different networks. The analysis and visualization resources provided by Loki, such as network displays and statistical summaries, allow us to rapidly gain insight into the behavior of networked systems through the use of abstract or highly idealized models of those networks. Loki Toolkit has been used to create models for evaluating the effects of network topology on cascading failures [2], asset disruption impacts on network congestion in power systems [3], evaluate the structure and consequences of large-transaction financial networks [4] and to simulate social networks and the effects of changes in those networks on pathogen transmission [5]. The goal of this work is identification of potentially effective mitigation strategies for preventing or halting cascading events. This section has two examples: a network topology analysis and a social network analysis.

2.1.1. Network Topology Analysis Example

The purpose of this analysis was to evaluate the impacts of network topology on cascading failures in an unregulated power market. For this analysis, a power grid is represented by two ideal network topologies that "bracket" what is found in real systems: regular fish-net lattice and scale-free (illustrated in Figure 3). In this model, sources and sinks are assigned representative values for power grids. DC circuit analogy is solved on the network to yield loads at each node and then nodes are given failure loads specified by a uniform safety factor (excess capacity) representative of grid design.

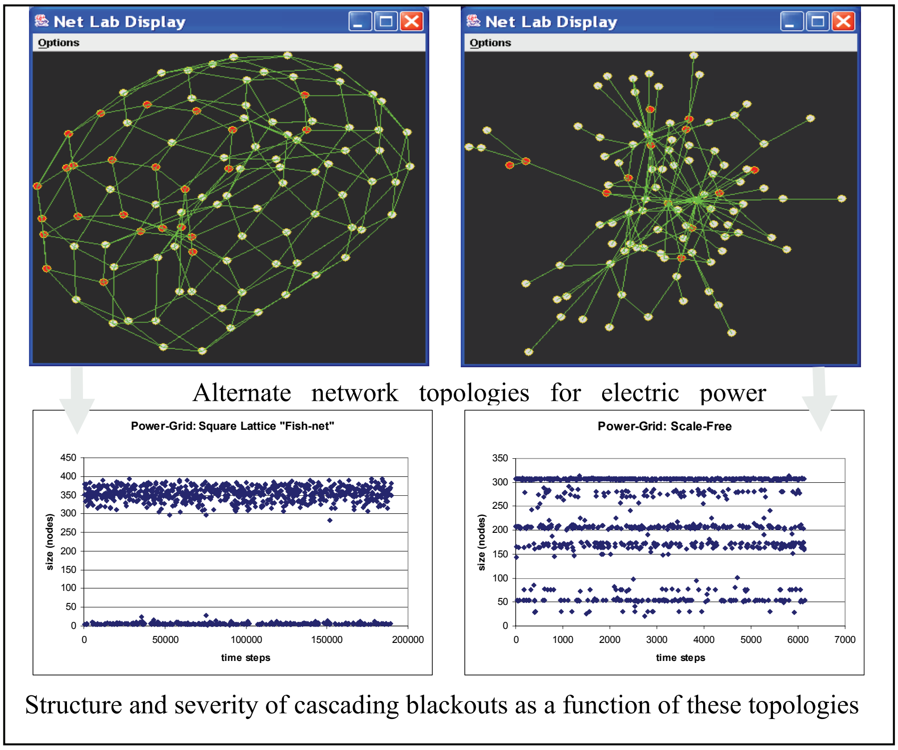

Figure 3. Loki generated network models for a direct current power grid and results of cascading failure analyses [2]

The system is driven by a random, unregulated market where pairs of sources and sinks are chosen at random to buy and sell electricity. After each transaction, load is recalculated within the network. This sequence continues until a node is pushed above failure threshold. The failed node is then removed, load is recalculated, and nodes which are now pushed above threshold then fail and are removed. The resulting load based cascade is followed to its completion and the cascade size (the number of nodes that fail) as a function of time is recorded. Hundreds of simulations are run. The results for two example networks each containing 400 nodes are shown in the plots at the bottom of Figure 3 where the y-axis is the cascade size and the x-axis is the total time required to generate and complete a cascading failure.

In the fishnet topology cascades are either very small, or near the size of the system. In the scale-free topology, the sets of cascades occur that are specific to a given network realization and determined by the specifics of the network topology. With a scale-free topology, the cascade causes natural breaks that fragment the system. The time scales for the two networks differ by more than 2 orders of magnitude, suggesting the fish-net to be much more robust to market perturbations than the scale-free (i.e., it can accumulate many more perturbations before cascading); but when it fails, essentially the entire network fails.

2.1.2. Social Network Analysis

The NISAC team is currently evaluating the potential impacts of an influenza pandemic. We are simulating impacts on the population (deaths, illness, and changes in behavior), how those impacts propagate to infrastructures and other businesses, and the economic effects caused by all those changes. Once again, the goal of this work is to evaluate the potential effectiveness of a wide variety of strategies for mitigating these consequences. Loki-Infect, a social network model for evaluating disease cascades, is being used to identify and evaluate local mitigation strategies for containing the disease spread. A relatively simple model of a small community of 10,000 people that fall within 4 age categories is used to look in detail at the social dynamics within 5 activity categories (home, neighborhood, work, community, seniors, and school). The community and household compositions conform statistically to the 2000 U.S. Census data. The number of contacts between individuals varies by age class and activity. Children and teens have the greatest number of contacts of the age groups. The typical group interactions and individual-to-individual relationships for a typical teenager (T1) in the model are illustrated in Figure 4.

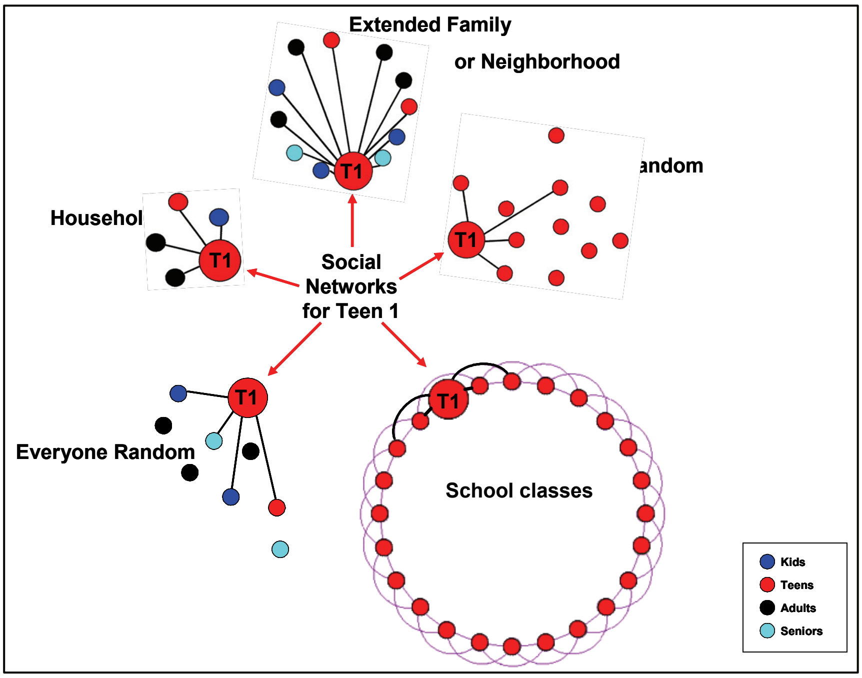

Figure 4. Teen social networks: In this model, teens have a mean contact frequency of 6/day in their fully-connected household, 1/d in their fully-connected neighborhood, 6 classes per day with 2 contacts per class in their ring-network at school, and random contacts 1/day with 3 another teens in the community and a random contact in the community once every 25 days (0.04/day).

The structure of the community's social network and the assumption that for pandemic strains of influenza teens and children are both more susceptible and more infectious than adults and seniors, means that any action that reduces the number of physical contacts teens make on a daily basis or decreasing their susceptibility would reduce the rate of spread of a contagious disease. Simulating the outbreak and spread of influenza with different disease characteristics and different strategies for reducing contact rates provides and indication if strategies that target one age group will be effective in reducing the number of epidemics, deaths, people ill, lost work days, and/or delaying the pandemic stage long enough to develop vaccines and distribute anti-viral medications. For the mitigation strategies that have been simulated so far, the most effective are: 1) closing schools and keeping 70 percent or more of the children and teens at home until the pandemic strain dies out, or 2) having a supply of vaccine that is effective enough to reduce the susceptible teens and children by 60 percent. Both of these strategies reduce the number of deaths, peak infected and total infected by more than 90% over the unmitigated case. The teen/child vaccination strategy is the most effective in reducing all the consequences (delays time to peak and reduces the duration of the outbreak) and is the only strategy that reduces the number of simulations that reach epidemic proportions by more than 50 percent (77% reduction). In the absence of sufficient supplies of vaccine, the local social distancing strategy of keeping children and teens at home should be considered one of the best mitigation strategies if a highly lethal pandemic strain of influenza develops.

2.2. System Dynamics Models

NISAC analysts use system dynamics modeling to quantify and evaluate the effects of infrastructures and their interdependencies on supply and demand under different conditions (e.g., time of day, time of year, unusual event, terrorist threat, natural disaster, new regulations, incentives, market structures). Dynamic simulation modeling allows analysts to identify and quantify consequences for evaluating risks; identify limiting factors and how they change under different conditions; evaluate the effects of system redundancies (alternate routes, alternate modes, product and/or equipment inventories); identify the potential magnitude, location and timing of disruptions that propagate to other infrastructures and regions; and both positive and negative effects created by interdependencies and their net effect on the supply-demand balance.

System dynamics models have been developed to evaluate U.S. infrastructures at a national, regional and asset level. The NISAC national petroleum system model simulates all the major system processes from imports and production of crude oil, through storage of crude oil, refining and storage of products, to the distribution and demand for refined products at a regional level (Figure 5).

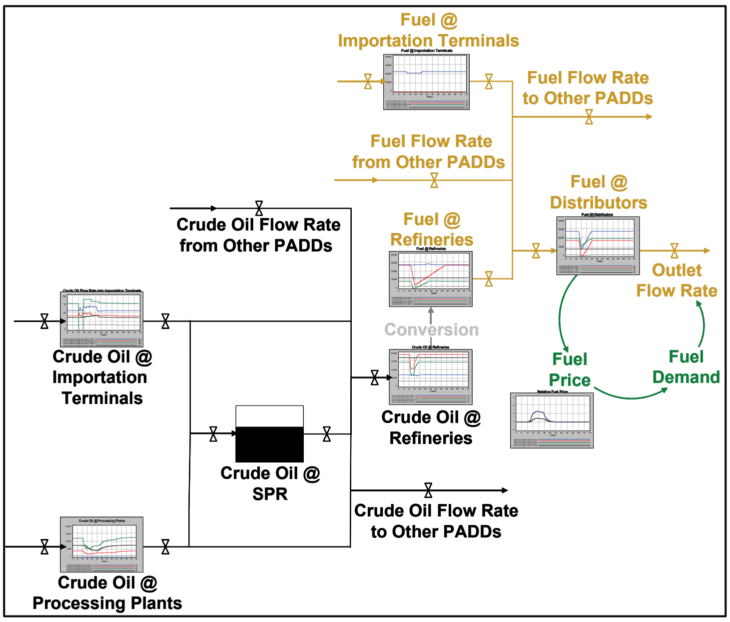

Figure 5. High-level overview of the major processes in the national petroleum model (PADD is the petroleum area defense district regionalization used in the model)

The national-level natural gas system model has a similar structure, modeling the production, storage, distribution and demand for natural gas. These models have been used to evaluate the potential impacts of hurricanes on supplies of gasoline and natural gas, compare the relative impacts process and asset disruptions, evaluate the potential impacts of the loss of crude oil tankers, demonstrate the benefits of distributed storage and evaluate the benefits of increased pipeline capacities.

The importance of international trade and the maritime infrastructure to our nation's economic health is one area of focus for our analyses. The NISAC Port Operations (Figure 6) and Port Economic Simulators were developed to evaluate the potential impacts of changes in port security measures on the flow of shipping containers through specific port facilities and their long-term economic competitiveness. The port models have been parameterized to represent the container terminals in Portland Oregon, Seattle Washington and Houston Texas.

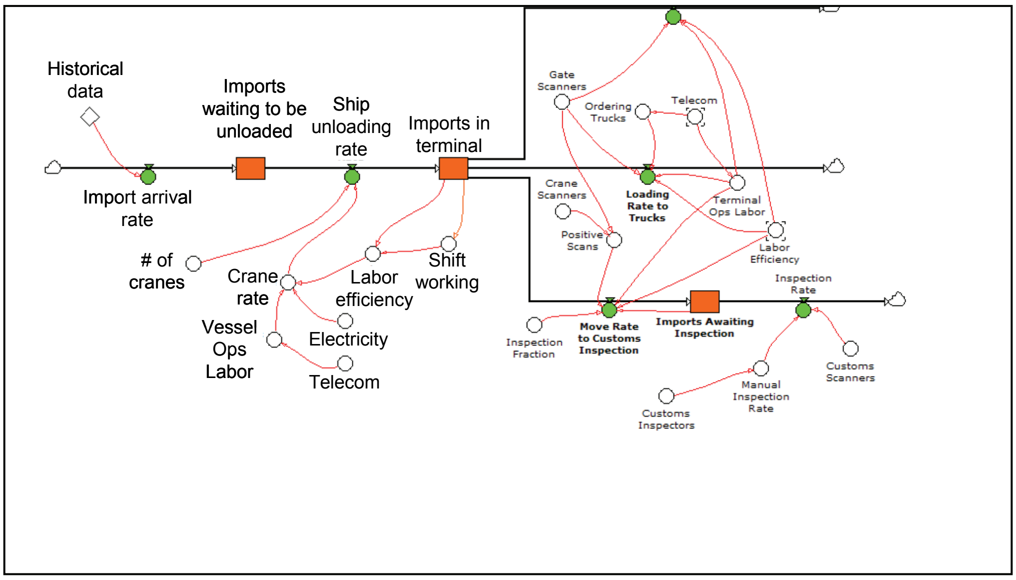

Figure 6. Simplified diagram of the port operations model showing the flow for import containers

The port simulators provide an opportunity to uncover potential problems in port-related national security and international trade policies before implementation and to begin to discover viable solutions before problems occur. The port operations simulator is being used to evaluate the impacts of labor shortages on infrastructures, as part of the avian influenza analysis.

3. Realistic Models

Detailed, more realistic models are needed to evaluate the details of the distribution of impacts due to losses of individual assets and larger-scale events such as natural disasters. Understanding of differential impacts and heterogeneous distribution of impacts is essential for building confidence the models and for refining policies and protective measure designs. These models require current and accurate data about the components and operations management in order to be realistic and not just highly detailed models with lots of knobs to turn.

3.1. Network Models

Many critical infrastructures can be represented by a network of interconnected nodes and links. Mathematically sound non-linear optimization techniques can then be applied to these networks to understand their behavior under normal and disrupted situations. Network optimization models are particularly useful for evaluating transportation system disruption effects on system capacity and the effectiveness of measures to reduce those impacts.

The railroad network analysis system (R-NAS) was developed to evaluate how the loss of one or more rail assets would impact rail operations, if the disruptions to rail transportation would impact national security, regional economic output or public health and safety. Using a detailed layout of the primary rail tracks, yards, bridges and other rail facilities in the continental U.S., coupled with commodity movement data from the Department of Transportation, R-NAS provides a capability of studying and understanding the flow of commodities over the nation's rail infrastructure. The network flow models predict commodity flow volumes over each link in the rail network and the corresponding transport times and distances for each commodity origin and destination pair. After disruption of a given rail asset, the model attempts to find alternate routes for the delivery of commodities. Delivery time constraints can be placed by the user to determine acceptable delays in delivery times, and the model can provide breakdowns of the types of commodities that do not move given the specific disruption in a scenario. The results for the analysis of impacts of Hurricane Katrina on rail transportation are shown in Figure 7.

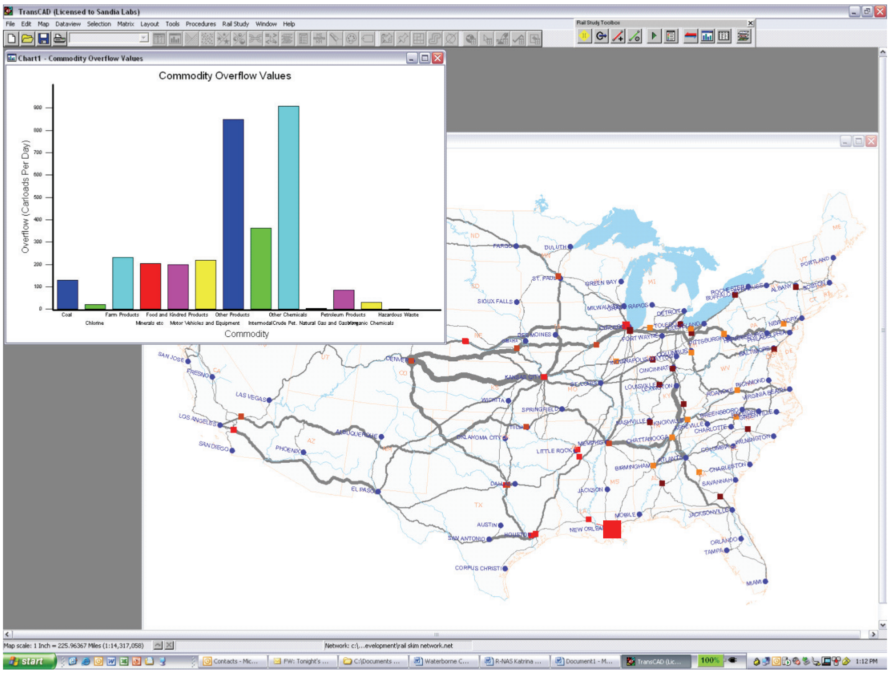

Figure 7. Estimated rail transportation disruption due to Hurricane Katrina in 2005

This approach is currently being applied to the air transportation network and telecommunications networks at the local and national level [6]. The Air Transportation Optimization Model (ATOM) is designed to evaluate the consequences of a partial or complete outage at a major airport or set of airports for an extended period of time. It can be used to determine the optimal re-routing scheme to minimize lost capacity and to estimate the distribution of impacts due to the disruption and re-routing. All of the transportation network models are being used to evaluate potential capacity changes in the event of an influenza pandemic.

3.2. Micro-Economic Models

One of the major consequences of a terrorist attack, pandemic or natural disaster is the economic changes that occur. Macro-economic models provide a useful set of tools for describing the economic activity that has been or could be disrupted by the event, but they don't provide any indication of the change in the ability to do business or compete economically in the altered environment. The NISAC Agent-Based Laboratory for Economics™ (N-ABLE™) is a large-scale microeconomic simulation tool that captures complex internal supply chain and market dynamics of businesses in the U.S. economy and is designed to answer economic policy questions through the simulation of thousands to millions of interacting firms.

Analyses based on N-ABLE™ simulations have evaluated the potential impacts of changes in U.S. border security technologies on domestic firms, impacts of terrorist attacks on commodity future markets, and transportation disruption impacts on regional food supply chains and national chemical supply chains. In the micro-economic analyses the distribution of impacts is evaluated to see how they vary spatially, temporally and by firm size (or other constraining characteristic). The goal of the analyses is to refine the policy or mitigation strategies to reduce the impacts not just in aggregate, but at all levels. The chlorine transportation disruption analysis provides a good example of the types of insights that can be gained using this level of fidelity in the modeling.

Figure 8 shows the model of 3,300 chlorine related firms and 15,000 links simulated in the chlorine transportation disruption analysis. The model included individual chlorine producers, markets created by chlorine consumers (chemical plants (inorganic, organic), manufacturers (PVC, pulp and paper), and water treatment systems), and chlorine transportation. For those businesses that receive chlorine shipments by rail, the disruption impacts the ability of the largest users to continue operations, leaving mid-size and small firms to supply the market with chlorine-based products (Figure 9). In evaluating the potential mitigation options, it was found that changing the rail transport policy to allow expedited shipments of chlorine reduces not only the recovery time from the transportation disruption, it reduces the number of chlorine rail cars on the rail network at any given time (Figure 10).

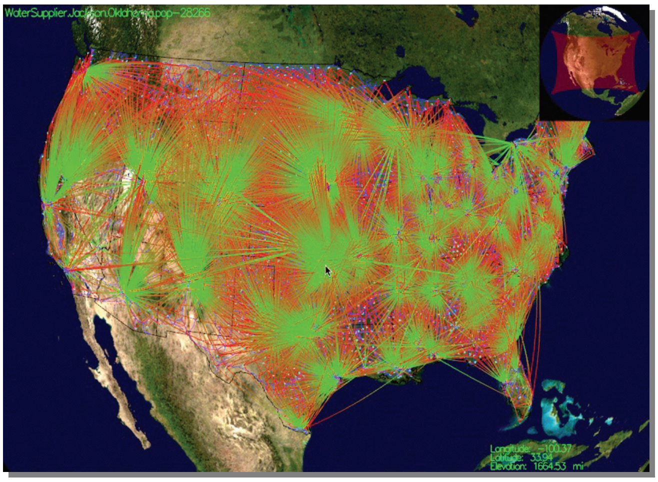

Figure 8. N-ABLE^{TM} Chlorine producer (green) and consumer (red) relationships

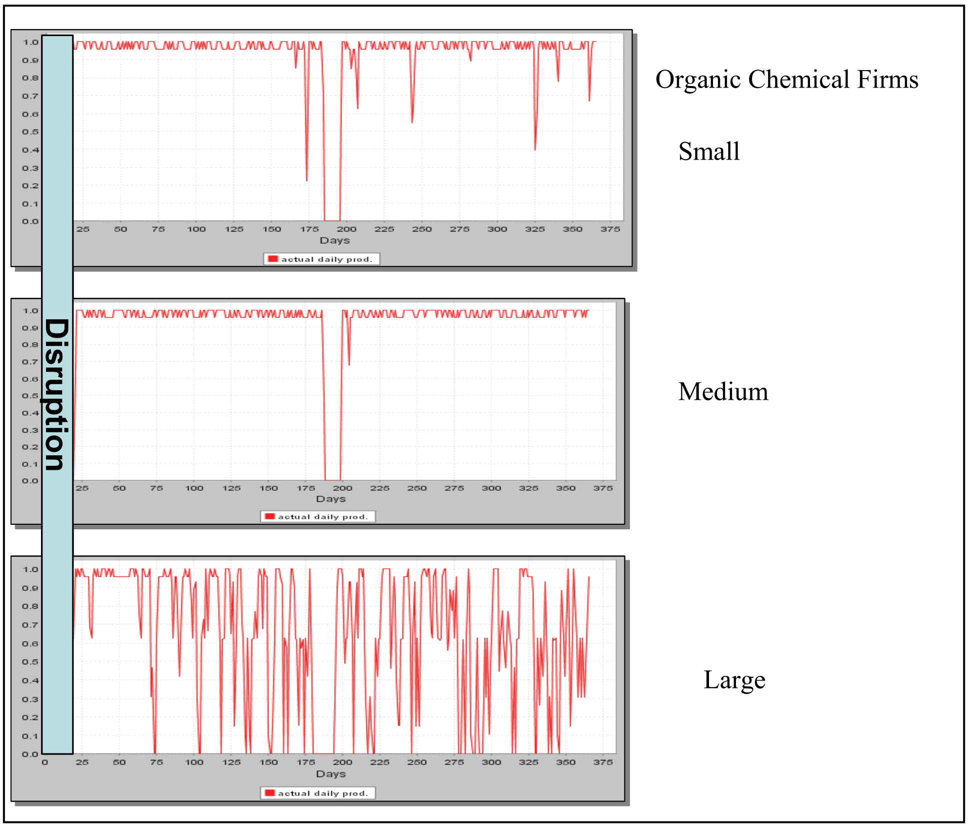

Figure 9. Results of the chlorine transportation simulation - production output levels for organic chemical firms (aggregate output by firm size)

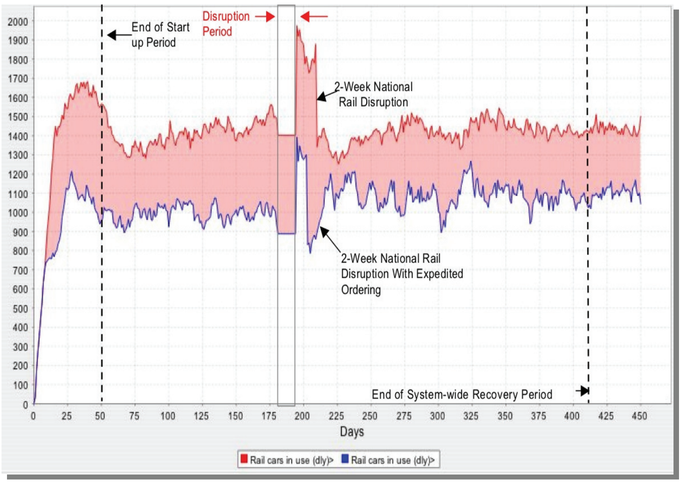

Figure 10. Results of the chlorine transportation disruption and mitigation analysis (number of rail cars on tracks is shown on the y-axis and the number of days into the simulation are shown on the x-axis)

4. Summary

The information presented in this paper is a brief summary of the results of six years of model development at NISAC; including examples of the types of models developed, their utility in answering critical infrastructure protection questions and insights regarding infrastructure behaviors, propagating effects of disruptions and potential effectiveness of consequence mitigation measures. Infrastructure interdependency analysis is a relatively new field of study. This work represents the beginning stage of modeling to understand these systems and their interactions at a national, regional and local scale under a wide variety of conditions.

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