Modeling Interdependencies between Power and Economic Sectors using the N-ABLE™ Agent-Based Model

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Abstract-- **The nation's electric power sector is highly interdependent with the economic sectors it serves; electric power needs are driven by economic activity while the economy itself depends on reliable and sustainable electric power. To advance higher level understandings of the vulnerabilities that result from these interdependencies and to identify the loss prevention and loss mitigation policies that best serve the nation, the National Infrastructure Simulation and Analysis Center is developing and using N-ABLE™, an agent-based microeconomic framework and simulation tool that models these interdependencies at the level of collections of individual economic firms. Current projects that capture components of these electric power and economic sector interdependencies illustrate some of the public policy issues that should be addressed for combined power sector reliability and national economic security.**

Index Terms—**Infrastructure interdependencies, electric power sector, economic impacts, policy analysis.**

I. Introduction

The U.S. Department of Homeland Security focuses its efforts not only on the physical security of the nation's cities and citizens but also on the security of the national economy. Since most U.S. economic sectors are heavily reliant on multiple infrastructures − most commonly electric power, transportation, and telecommunications − a critical factor in economic security is *infrastructure surety*, or the safety, security, reliability, and continuity of operations of these infrastructure. Prior to the terrorist attacks of September 11, 2001, the potential for infrastructure disruptions was often evaluated in terms of engineering tradeoffs that had been made between economic efficiency and system reliability. After the attacks, these same infrastructures began to be additionally evaluated in terms of surety against disruptions caused by man-made disasters, and to be comprehensive, natural disasters as well.

Investigation of these vulnerabilities led to the realization that many of the nation's critical infrastructures are *interdependent*: a disruption in even a single infrastructure can rapidly propagate through multiple infrastructures, thereby originating disruptions in each. For example, economic firms depend on a reliable banking and finance sector, which itself depends on reliable telecommunications and electric power. Since the power sector relies on the telecommunications sector and vice versa, an attack to either power or telecommunications could shut down the other, as well as the banking and financial sectors and ultimately the economic firms. Given the specific remarks Osama bin Laden has made about hurting the U.S. by attacking its economy,[2] its plausible that terrorists could design an attack that causes a disruption in a single infrastructure and, by propagating through multiple infrastructures, shut down a significant part of the national economy. While direct attacks on U.S. consumers' confidence may be more likely means of attacking the economy (such as increasing people's fear of, and later inconvenience of, flying), infrastructure attacks are potentially highly effective means of attack.

Ten years ago researchers at U.S. Department of Energy laboratories and other facilities began investigating the extent to which these infrastructures are interdependent, that is, how they mutually require from one another the continuity of their respective infrastructure operations. In 2000, the National Infrastructure Simulation and Analysis Center (NISAC) was founded to accelerate the development and use of advanced modeling and simulation capabilities that analyze the interdependencies and vulnerabilities in the U.S. critical infrastructures. Funded by the U.S. Department of Homeland Security (DHS), NISAC aids decision makers in infrastructure policy analysis, investment and mitigation planning, education and training, and crisis response. The NISAC tools include highly aggregated models of the nation's critical infrastructure, detailed urban models of key infrastructure sectors, reduced-form infrastructure and economic models designed for fast-turnaround analyses, and high-fidelity regional and national economic models.

II. NISAC Agent-Based Laboratory for Economics (N-ABLE™)

One of NISAC's tools, N-ABLE™, is a high-fidelity agent-based microeconomic framework and tool designed to analyze the interdependencies between economic firms and the infrastructures they use. N-ABLE™ models individual firms, households, government authorities, and other fundamental economic entities as agents in an economy that interact via infrastructure, markets, and other means important to modeling infrastructure interdependencies.

A. Architecture

As shown in Figure 1, each N-ABLE™ EconomicAgent firm is composed of buyers, production supervisors, sellers, and strategic planners who conduct their real-world analog tasks within the enterprise and between enterprises. Many of these tasks (ordering, receiving, selling, shipping, producing, etc.) rely on specific infrastructure sectors: buyers and sellers

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[2] In a video tape (circa 2001) calling for Jihad against the United States, bin Laden declared, "we can destroy the American empire by destroying its economy," and, "[make] frequent attacks on America's economy where that country is most vulnerable."

use the electric power, telecommunications, and transportation infrastructures, and within-firm production relies on electric power and telecommunications; different types of infrastructure disruption therefore can have different impacts to the firms. Using N-ABLE™'s generic data-driven object structure, firms representing a range of economic sectors (e.g., manufacturing, financial, household) can be modeled by specifying such things as particular production functions, buying and selling behavior, inventory capacities, and long-term strategic planning.

Entire economies of firms and households are constructed from this enterprise design, each interacting with others through markets and physical infrastructure. For example, in Figure 2 a collection of EconomicAgent-based manufacturing firms in the center of the figure sell and ship product to intermediate EconomicAgent packagers in an inner collection of regional firms, who then sell final production to end-use EconomicAgent firms in the outer collection of regional markets. Each group of firms uses electric power and transportation infrastructures and is affected economically by their disruptions and interdependencies. These simulations of thousands to hundreds of thousands of firms provide the fidelity necessary to understand how individual firms, and regional economies composed of them, are affected and interdependent with electric power and other critical infrastructure.

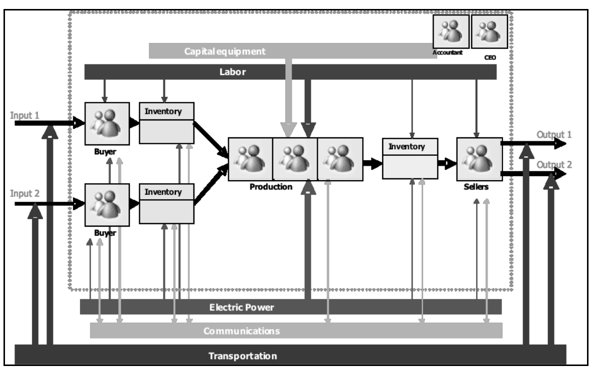

Figure 1. Structure and infrastructure dependencies of the N-ABLE™ EconomicAgent.

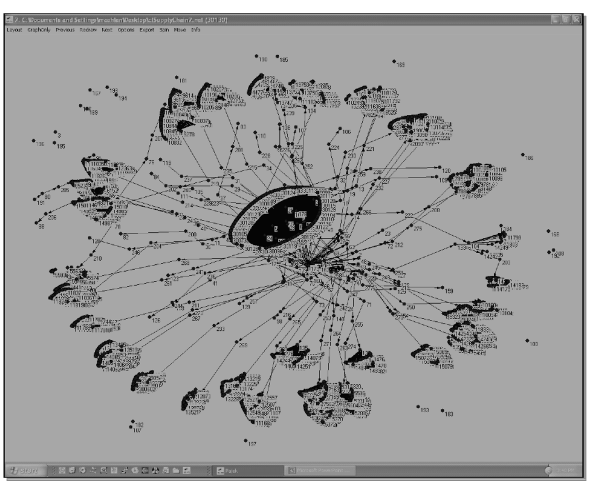

Figure 2. Network Representation of an Economy of EconomicAgents

Depending on the complexity of the infrastructures being modeled, the infrastructures themselves are either modeled internally within N-ABLE or externally. When done externally, the combined N-ABLE/infrastructure model is run as a distributed simulation in which N-ABLE communicates in real time with the other model using Web Services or faster Unix-level data transfer mechanisms.[3]

At the core of N-ABLE™ is a hierarchical model of microeconomic firms, households, and other microeconomic entities and an extensible C++ architecture that makes possible (1) rapid development of new types of firms, households, and infrastructure; (2) the real-time distributed simulation with third-party transportation, electric power, and other network models; and (3) "human in the loop" simulations, where one or more analysts participate as agents.

B. Questions to be Addressed

In the context of infrastructure interdependencies and economic security, N-ABLE™ is designed to answer the following high-level questions:

- What economic sectors are most vulnerable to infrastructure disruptions and interdependencies? Sectors have different usages of energy, transportation, financial, and communication services, as well as different second and third order impacts from disruptions.
- Within economic sectors, what firms are most affected? Which ones do well, and which do poorly? How do firms, individuals, and other economic components respond, over time and over regions?
- How do the infrastructures themselves inhibit or accelerate the mitigation of economic damages? What short-run economic changes affect infrastructure performance, before, during, or after a disruption?
- What public policies do national, state, and local governments have to assist firms to prevent and mitigate losses from infrastructure disruptions? What equivalent strategic management options exist for private industry? What are the relative efficacies of these options?

C. Modeling Advantages

N-ABLE™ – and agent-based modeling in general – provides a number of unique benefits in simulating economic-infrastructure systems. N-ABLE™ models these systems as large-scale Markov processes in which economic actors and their infrastructures "self-assemble" into a baseline state. (This baseline is typically a set of irreducible states, or a minimum subset of the complete state space of the system.) This initial, transient period of economic-technical assembly gives analysts insight into some of the dynamics not only of how new economic-infrastructure systems could initially evolve,

[3] Distributed simulations have been conducted between N-ABLE and the Argonne National Laboratory agent-based EMCAS model, and between N-ABLE and the Sandia system dynamics model of the California oil/gas/electric power system.

but also some of the means by which economic-infrastructure systems recover from disruptions.

Second, simulations can suggest whether there are path dependencies in the economic-infrastructure system. After an infrastructure disruption, the system may eventually return to its baseline state, or instead take any number of alternative paths that are inferior or superior to the baseline state. Markov process-based systems that return to the baseline regardless of the initial conditions of the disruption do not depend on any particular initial conditions of the disruption. In contrast, systems that instead take any number of post-disruption paths are very sensitive to initial conditions. Furthermore, systems can exhibit *punctuated equilibria*, where the system categorically changes performance for short intervals and then returns to its previous state. By analyzing the path dependency and punctuated characteristics of the system, analysts can better understand both the vulnerabilities inherent to the economic-infrastructure system as well as its ability to self-heal.

D. *Simulation Capabilities*

N-ABLE™'s data-driven, high-fidelity parallel computing architecture is designed for analysis of thousands to millions of economic firms and households that are affected by infrastructure changes on the order of days to months. Coupled with Sandia's large institutional computing clusters and uncertainty quantification software such as DAKOTA,[4] comprehensive sensitivity analysis can be conducted of the likelihood of significant impact from infrastructure and economic disruptions. In addition, work is currently being done to integrate optimization procedures (e.g., mixed integer linear programming) to aid in investigating how logistics centers and other centralized information systems affect the economic-infrastructure system.

III. Recent Projects

N-ABLE™ is currently on a five-year plan for completing development of the architecture necessary for modeling the economic-infrastructure system in sufficient microeconomic detail. This plan includes development of not only the required economic functional forms for firm production, household consumption, and markets, but also their connections with physical infrastructures. As illustrations of ongoing work that motivates and validates this plan, the following projects highlight some electric power-related projects that have used N-ABLE™.

A. *Impacts to Supply Chains of Electric Power Disruptions*

Work was conducted for DHS to analyze the economic impacts to particular chemical industries of disruptions to both electric power in the Gulf Coast region and to national rail transport. Using industry data on over 3,000 firms that manufacture, transport, repackage, and use this chemical, detailed N-ABLE™ simulations were conducted of intra-firm and inter-firm supply chain impacts of regional electric power and transportation disruptions that ranged in duration from three days to 8 weeks. Figure 3 shows the locations of the agents in this simulation and, in the lower right corner of the figure, shows a particular end-use market.

Figure 3. U.S Chemical Supply Chain

Among the key findings, the work found that, for even a one-week electric power disruption, it took four to six weeks for the chemical supply chain to return to its baseline, fully utilized state. Several economic factors cause this prolonged delay: first, since the chemical supply chain is typically at capacity, there is simply not enough additional production to restore buffer stocks at intermediate- and end-use stages of the chemical value chain, leading to the stochastic starving of productions as inventory levels fluctuate more widely. Second, since the railcars that carry the chemical are specially constructed and regulated for this particular chemical, they are typically all in use. Hence, even if there were additional product to ship, there are no rail cars ready and available at the correct locations to ship it in.

In this particular disruption, the limited railcars are the binding constraint, reducing both chemical production, and consequently, electric power needs. The implication for the electric power industry is that even if their own production capacity is restored immediately after a relatively short disruption, their sales and related profitability could be reduced for significantly longer periods of time. If in the extreme case the regional power sector is economically vulnerable to this reduced sales and profitability, the end-use economic sectors could be affected economically as well.

B. *Residential Real-Time Pricing Contracts*

A number of regional and national power authorities are considering residential real-time pricing (RTP) contracts for managing end-use power demand. Adding RTP contracts to residential sector will reduce aggregate peak-hour power usage, but could the resulting power use shifts be large and unpredictable enough to undermine grid stability? More generally, how would power system changes affect power system and economic stability?

As part of work for Consortium for Electric Reliability Technology Solutions (CERTS), we generated N-ABLE™ household agents that consume power through either the current uniform price (UP) or a hypothetical real-time price

[4] For more information on DAKOTA, see http://endo.sandia.gov/DAKOTA/.

contract. Using data on California residential power demand by usage (e.g., refrigerator, drying, TV), we grouped household power usage into three types: movable, immovable, and discardable. Given the right RTP price incentives, their utility budgets, and their fundamental willingness to adjust power usage, households reschedule movable power usage and discard some of the discardable power usage.

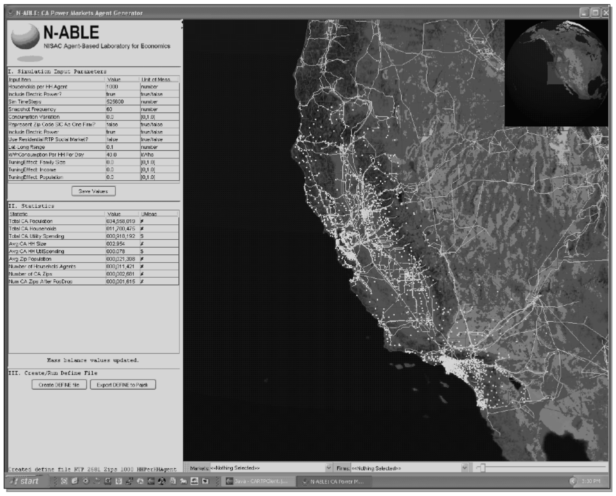

Figure 5. California Residential Power Sector

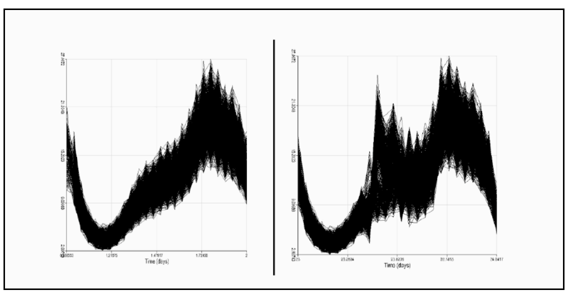

Figure 6. Residential Diurnal Power Usage: Uniform Price and RTP Contracts

The work generated three main findings. First, using reasonable estimates of rescheduling of electric power, the residential diurnal power usage profile could change as in Figure 4, where the new peak residential demand occurs in two places: later in the evening and earlier in the day. Second, if households experienced true real-pricing, then cyclic patterns of residential power usage could occur (two new load peaks create two new price peaks, which then cause households to move power back between the peaks, and so on), ultimately motivating power utilities to offer a simpler price profile such as a two-tier pricing schedule. Furthermore, when the power utilities pass wholesale price spikes on to the households, these spikes are often enough to cause mass household defection from RTP contracts back to UP contracts. Thirdly, if the households are not bound to RTP contracts over fixed periods, e.g., 12 months, then power utilities that aggressively pursue RTP contracts for the purposes of being the first to have excess transmission capacity during peak-load hours (for which they can generate unregulated, supra-normal levels of profit), could experience mass defection from RTP contracts back to UP contracts, in which case this same power utility would likely have to purchase either additional peak-load power, or transmission capacity, or both, from other Transcos at these supra-normal rates. Without careful planning and testing, introduction of this type of contract could introduce new economic vulnerabilities to the power sector.

This work is currently being extended to analyze how two-tier price and *critical peak price* RTP contracts could affect aggregate California peak-load demand, regional peak-load transmission needs, and economic vulnerabilities for Transcos. Figure 5 shows the zip code-level distribution of these N-ABLE™ households and the supporting electric power infrastructure. The likely implication of two-tier pricing is that it will reduce the level of peak-load demand, but do little to provide demand response during wholesale price spikes; for this, critical peak pricing is a viable mechanism, and testable via agent simulations.

C. Multiple Spot Markets For Electric Power

Finally, in 1998 Sandia began theoretical studies of the impacts of price caps in power spot markets.[5] The simulations were composed of three main players – buyers, sellers, and the market settler or auctioneer – and supporting commercial, industrial, and consumer economic sectors. Buyers of spot power submitted (P,Q) buy bids to the settler while sellers submitted (P,Q) sell bids; the settler determined the market clearing price (MCP) based on submitted bids, following market rules, e.g., the settlement price P* could not exceed the price cap if one existed. Sellers had expectations for profit that were driven by demand, e.g., the more high-demand days there are, the more profit they expect.

The primary finding of the work is that price caps on energy markets can in fact lead to *higher* clearing prices. This results from sellers who, given their internal expectations of annual revenue and profit, find that increasing their off-peak bidding prices is a necessity in order to make up for lost expected profits during peak-of-peak demand hours, thus leading to higher costs overall (on the order of 5-6 percent). This is essentially the 'insurance premium' of doing business with a price cap. These results matched well with the performance of the California market, where once price caps were altered in mid-stream from a maximum of $750/MW to $250/MW, all power began to trade at the price cap. At a policy level, efforts then to reduce the cost of power to end-use economic firms have the potential for the opposite effect; while not analyzed within this work, the economic impacts could be significant and therefore impact future power sector needs.

IV. Summary

The electric power sector and the economic sectors they serve are highly interdependent; vulnerabilities in one sector that have the potential for economic or technical disruption, an clearly explicit disruptions, can cause extended changes in the other sector. In support of the Department of Homeland Security's mission of insuring the nation's economic security through loss prevention and mitigation, NISAC is developing N-ABLE™, a detailed microeconomic simulation framework

[5] The simulations were run in 2000 and used the Sandia Aspen-EE model, the precursor to N-ABLE.

and tool that models how economic firms and households use electric power and other infrastructure to conduct their economic business. N-ABLE™'s cellular, enterprise structure allows for detailed understandings of the intra-firm, inter-firm, and firm-infrastructure dynamics causes by man-made and natural disruptions to the electric power, telecommunications, and other critical infrastructure. The work conducted thus far on the interdependencies between the power sectors and economic sectors indicates that these interdependencies are real and their impacts can be significant, often in ways that are complex and not readily understood.

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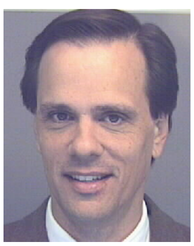
BIOGRAPHIES



Mark A. Ehlen graduated from Cornell University with a Bachelors of Science in Engineering (1983) and Doctorate in Economics (1996). His employment experience includes the National Institute of Standards and Technology, where he was awarded the Department of Commerce Bronze Medal, and Sandia National Laboratories. His fields of interest include the economic impacts of new technologies, economic networks, agent-based modeling, and complex adaptive systems.

Andrew J. Scholand received a B.S.M.E. with high distinction from Worcester Polytechnic Institute in 1989. After a year volunteering in Southern Africa installing solar panels, he obtained a Masters Degree in Electrical Engineering from Kings College London, graduating third in class. He returned to mechanical engineering for his Ph.D. at the Georgia Institute of Technology, focusing on analysis theory and methodology in computer aided engineering (CAE). At Georgia Tech, Andy held dual fellowships from the Department of Energy (Integrated Manufacturing Fellowship) and the state of Georgia (Georgia Tech President's Fellowship). Andy graduated from Georgia Tech in 2001, and joined Sandia National Laboratories 6 months later. He is currently Deputy Team Lead for the Computational Economics group, where he pursues interests in large-scale simulation, software development, and the application of complex adaptive system theory to real-world problems.