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Toward Modeling and Simulation of Critical National Infrastructure Interdependencies

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Abstract

Modern society is dependent upon a complex network of interdependent critical infrastructures. Continued prosperity and national security of the U.S. depend on our ability to understand and analyze this complex network, and to timely and effectively respond to potential disruptions. In this paper, we propose an innovative modeling and analysis framework for interdependent critical infrastructures based on system dynamics, IDEF, and nonlinear optimization algorithms. Collaborative efforts among Sandia, government agencies including DHS, commercial/private industries, and academics have resulted in realistic models, including critical infrastructure models, e.g. power, petroleum, natural gas, water, and communication, and economic sector models, e.g. residence, industry, commercial sector, and transportation. The proposed framework and models are demonstrated for hypothetical disruption of a critical infrastructure and optimal response.

1. Introduction

The continued prosperity and national security of the U.S. is dependent on reliable operation of the complex network of interdependent, large-scale critical infrastructures. The impact of capacity excess or disruptions of them on defense and economic security of the nation would be devastating. Therefore, our ability to model and analyze them is of critical importance

to timely and effectively respond to potential disruptions. Although efforts to understand the interdependences of the critical infrastructures have taken on increasing importance during the last decade, it was learned that modeling and analysis of them is an extremely difficult task. This is because 1) data acquisition is difficult, 2) each individual infrastructure itself is very complicated, 3) infrastructures evolve and the regulations governing their operation change, and 4) it is impossible to construct a realistic model without a leading role of a government agency coordinating commercial/private industries.

More recently, Sandia National Laboratories have collaborated with government institutions, industries, and academics to understand the potential consequences of infrastructure interdependencies. The goal of the program is to develop modeling and analysis tools for evaluating potential effects of disruptions of critical infrastructures and mitigating them under collaboration with other national laboratories and industries, and government institutions. In this paper, we first discuss an innovative modeling framework for simulation and decision support system of interdependent critical infrastructures based on system dynamics, IDEF, and nonlinear optimization algorithms. We then provide examples of how we apply them in a certain disruption scenario, where the key task is to allocate scarce resource of critical infrastructures.

The remaining sections are organized as follows. In Section 2, we discuss definitions, scope, and issues of critical infrastructures. In Section 3, the overview of methodologies used in this research is discussed. The modelling framework and experimental results with model are then presented in Section 4. Finally, conclusions are drawn in Section 5.

2. Interdependencies of Critical Infrastructures and Their Protection

U.S. Critical Infrastructure Assurance Office defines an infrastructure as "the framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services and services essential to the defense and economic security of the U.S., the smooth functioning of governments at all levels, and society as a whole" (Presidential Decision Directive 63). In this perspective, infrastructures include agriculture/food, drinking water, banking and financing, chemical industry and hazardous materials, defense industrial base, public health, emergency services, energy, government, information and telecommunication, and postal and shipping. More recently after the 911 terror attack, other key assets have been added into the consideration including national monuments and icons, nuclear power plants, dams, government facilities, and commercial key assets.

Critical infrastructure protection means not only protecting infrastructure itself but also protecting the services, physical and information flows, role and function and specially symbolized core values of the infrastructures. Criticality of the infrastructures can be either teleological or systematic. Teleological criticality means that an infrastructure is inherently critical, because of its role or function in society. An existential security policy objective can no longer be achieved in the event of the collapse of, or damage to the infrastructure. For example, the U.S. Congress and Whitehouse are attractive targets, not because they are connected in some way, but they are symbols of national power. On the other hand, systematic criticality means that an infrastructure is critical because of its structural positioning in the whole system of infrastructures and it is an important link between other infrastructures or sectors (Metzger, 2004).

In the real world, no infrastructure stands alone. If electric power distribution is disrupted and power goes off, then traffic lights go off and phone and email systems go off. Thus the electric power, transportation and communication infrastructures are linked and interdependent. Deliberate attacks or serious accidental system failures of one infrastructure may result in serious consequences to the nation because of the interrelationship among infrastructures and its potential cascading effects. Some of the infrastructures have the potential to impact many other infrastructures. Electric power and telecommunications influence the operational capacity or demand side for almost all of the other infrastructures, while all the infrastructures and demand sectors interact with and through the banking and finance system. Other infrastructures and sectors such as chemicals and hazardous materials, defense industrial base and key national resources tend to be impacted by infrastructure disruptions but do not tend to propagate the effects to other infrastructures or regions. The degree of connectivity through potential major interactions between each of the infrastructures is illustrated using a causal loop diagram (CLD) in Figure 1. The variables, which directly influence each other, are connected by directional arrows with a '+' or '–' sign. The sign '+' means that changes in the first variable cause changes in the same direction in the second variable; the sign '–' means that the first variable causes a change in the opposite direction in the second variable. The behavior of the entire infrastructure system is the result of the complex interrelationships among the various system variables. While the causal loop diagram depicts a high-level interdependency among variables, system dynamic (SD) models (see Figure 3) contain explicit equations (differential or difference equations) governing their relationships.

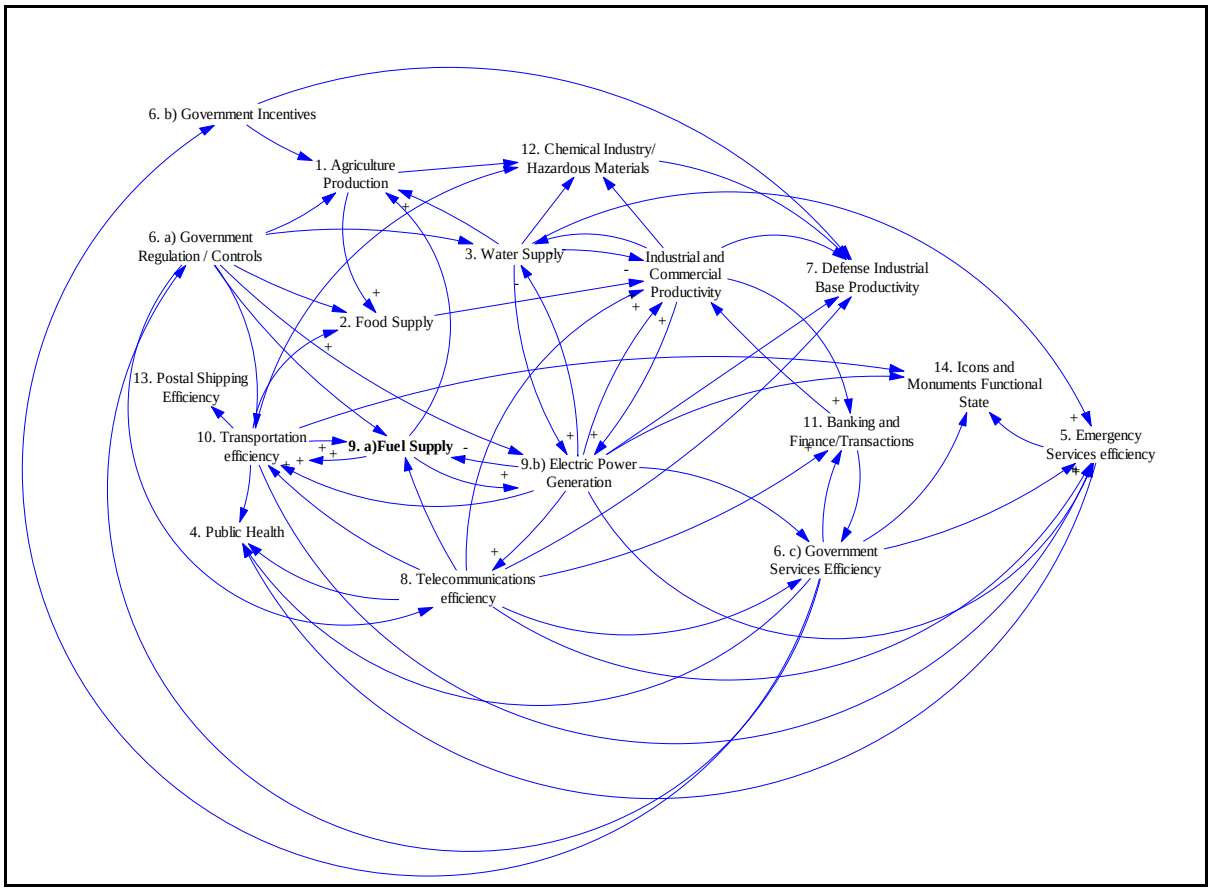

Figure 1: High-level infrastructure interdependency causal loop diagram

Rinaldi et al. (2001) classified interdependencies of infrastructures as four types: physical, cyber, geographic and logical. Physical interdependency means two infrastructures are physically interdependent on the material/service output(s) of the other. A commodity produced or modified by one infrastructure is input to another infrastructure for it to operate. In this type of interdependency, perturbations in one infrastructure can ripple over to other infrastructures. Therefore, the risk of failure or deviation from normal operating conditions in one infrastructure can be a function of risk in a second infrastructure if the two are interdependent. Cyber interdependencies connect infrastructure to one another via information links. Cyber interdependencies are relatively new and a result of the advanced computerization and

automation of infrastructures. The outputs of the information infrastructure are inputs to the other infrastructure, and the commodity passed between the infrastructures is information. The breakage of this information link between infrastructures may cause the physical flow of material/services between them. Geographical interdependency means that more than two infrastructures can be geographically interdependent based on their physical proximity. Events such as explosion or fires could create correlated disturbances in these geographical interdependent infrastructures. However, the state of one infrastructure dose not effect on the state of another. Logical interdependency means that two infrastructures are logically interdependent if the state of each depends on the state of others via human decisions and actions. For example, gas price low it results in increased traffic congestion. In this case, the logical interdependency between the petroleum and transportation infrastructures is due to human decisions and actions and is not the result of a physical process.

Modeling and analysis of critical infrastructures interdependencies are complex and challenging tasks for several reasons. First, the majority of the infrastructure is owned by commercial or semi-commercial interests, and acquisition of data and information is difficult. Private infrastructure owners should operate competitively using their limited capital investments and operational expenses. Safety and security of infrastructure components beyond what is required by regulatory authority and legal requirements are not their primary concerns compared to providing an immediate competitive advantage. Sharing or exchange of information required to maintain either interdependent elements of infrastructure or the entire infrastructure can put the civilian infrastructure owners at a disadvantage. This can occur when required information sharing in a given sector exposes business intelligence (e.g. cost structure, process capacities) to the competitors in the same or another sector. Therefore, the data and information collected and

exchanged in the interest of improving the robustness, availability, and overall assurance of infrastructure elements must be protected against malicious interests and influence (Wolthusen, 2004). In this work, Sandia has collaborated with Department of Homeland Security, other national laboratories, and commercial/private industries to develop realistic models. To the best of our knowledge, the models addressed in this paper are among the most comprehensive critical national infrastructure ones. Second, many models and computer simulations exist for aspects of individual infrastructures such as electric power networks model, traffic management models for transportation network, telephone call traffic analysis models, among others. However, simply hooking several existing infrastructures does not work; every model has its unique assumptions, data, and numerical requirements (e.g. time units, scaling limits or computational algorithms) that may not be compatible with other models. Further, such approaches do not capture emergent behavior, or a key element of interdependency analysis. Therefore, it requires more intensive studies of integration aspects of individual critical infrastructures such as matching time resolutions and data conversion and mapping between two critical infrastructure models based on time-step or requirements. In this work, IDEF∅ model (see Section 4) of the critical infrastructure has been developed to form a basis for the integration of individual infrastructure models. Last, each individual critical infrastructure has its own objective function such as minimizing communication traffics for communication infrastructures and promising secure transactions for banking and financing infrastructures. Some of objective functions of individual critical infrastructure might have conflicts, and could not be satisfied simultaneously. No single approach will address and meet all the different objectives of different critical infrastructures. Therefore, some ultimate global objective function, which is agreed with all critical infrastructure owners and users, has to be determined. In this work, we have developed a global

objective function from the perspective of a governmental mediator to minimize the impact on the whole society in the case of disruptions.

3. Overview of Methodologies

This section discusses an overview of three major methodologies used in this research for integrative modeling and analysis of interdependent infrastructures. They are system dynamics, IDEF system specification tool, and nonlinear optimization algorithms.

System dynamics (SD) is a method of for studying the dynamics of the real-world systems around us. Its key concept is that all the objects in a system interact through causal relationships. Three core factors that constitute a SD model include (Reid and Koljonen 1999): 1) the structure of the system, expressed in the form of feedback-based causal loop diagrams, 2) the frequency and duration of time delays in the feedback loops, and 3) the amplification of the information flows through the feedback structure. Simulations based on these factors can provide insight into important causes and effects, which can lead to a better understanding of the dynamic and evolutionary behavior of the system as a whole. They can yield a time-based plan based on a dynamic view of the system rather than a fixed plan based on static view of the system.

The causal loop diagram (see Figure 1), an abstract SD model, does not capture the stock an flow structure of the system (Richardson 1986, Richardson 1997, Sterman 2000, Binder et al. 2004), which is required to model the dynamic system exactly and derive the appropriate differential equations. Such a model can however be modeled as Stock and Flow Diagrams (see Figure 3; Sterman 2000), a more detailed SD model. System dynamics is particularly appropriate to model complex overall interactions for which very sparse data (if any) are

available. In addition, it can take randomness into account and enables a form of experimentation not possible in the real systems. Finally, it enables to gain insight into the stability of the system via transformation to the closed loop transfer functions (Disney and Towill 2002). However, explicit stability analysis is beyond the scope of this paper.

A formal system modelling technique has been employed to describe the proposed interdependency SD simulation model of the critical infrastructures and economic sectors. The purpose of a system model is to help define data requirements and describe the exchange of information between models. It lays down unambiguous guidelines that facilitates the development of a large scale, networked, computer environment that behaves consistently and correctly. In this work, functional modelling (IDEF∅, see Figure 4), a system description technique developed by the U.S. Air Force, is used to identify the system functions within the system, along with the flow of information and objects which relate the functions. The hierarchical nature of IDEF∅, the primary strength of the method, facilitates the ability to construct models that have a top-down representation and interpretation, but which are based on a bottom-up analysis process. Beginning with raw data, the modeller starts grouping together functions that are closely related or functionally similar. Through this grouping process, the hierarchy emerges (http://www.idef.com/ at KBSI). Modelling efforts in this research consider over 5000 variables and parameters, and therefore, we benefit from the hierarchical nature of IDEF significantly. As mentioned earlier, IDEF∅ model (see Section X) of the critical infrastructure has formed a basis to integrate individual infrastructure SD models in this work.

Once the integrative SD model of the critical infrastructure is constructed, we need to find the values for the input variables such that an expected system performance from the SD simulation is optimized. In this work, the objective function is to maximize total economic

revenue in the case of disruptions (see Section 3.1). Contemporary simulation optimization methods (Azadivar and Tompkins 1999) include (1) gradient-based search methods, (2) stochastic approximation methods, (3) sample path optimization, (4) response surface methods, and (5) meta-heuristic search method, including genetic algorithms, simulated annealing, and tabu search. In this work, we employ a suite of nonlinear optimization algorithms, which is combined into MINOS software package (Murtagh and Sanders 1998), since it is widely known and available. In MINOS, problems with linear constrains and nonlinear objectives are solved using a reduced-gradient algorithm (Wolfe 1962) in conjunction with a quasi-Newton algorithm (Davidon 1959). On the other hand, those problems containing nonlinear constraints are solved a projected augmented Lagrangian algorithm, based on a method due to Robinson (1972). To overcome the problems of local optimum, we start the optimizer in a number of different places. Performance investigation of different optimization approaches is important but is beyond the scope of this paper.

4. Interdependency Model of Critical Infrastructures and Optimization Problem

The integrative interdependency model of critical infrastructures simulates the effects of loss in capacity of an infrastructure on other infrastructures and economic sectors. Each infrastructure model includes the available capacity for the supply side of the system (production and transportation process) as a function of the maximum production capacity and reductions in that capacity due to damage of physical system or shortages of essential inputs (dependencies on other infrastructure services). The simulations are driven by historical demand time series that account for diurnal and seasonal variations in demand. Prices are modeled as a function of the ratio of supply to demand and demand elasticity functions that alter the demand in response to

price. In this section, we provide details of modeling critical infrastructure interdependencies using system dynamic simulation techniques.

4.1. Problem Definition and Model Description

In this study, the proposed interdependency simulation model of critical infrastructures will provide the capability to allocate the available infrastructure services or materials to each of other infrastructures and to economic sectors in order to minimize potential economic impacts of the given scenarios with various magnitude, extent, and duration of disruptions on an infrastructure. The notation used in the proposed model is shown below:

Notation:

L_i = capacity loss of critical infrastructure i;

CI_i = total available products/services of critical infrastructure i;

α_{ij} = satisfaction rate of desired consumption of Product/Service i for demand sector j;

D_{ij} = desired consumption of product/service i for demand sector j;

I_{ij} = available inventory of product/service i for demand sector j;

ER_j = economic revenues of demand sector j

R_{ij} = relative availability of product/Service i for sector j;

LA = labor availability;

AP_{ij} = allocated product/service i for demand sector j;

i = p(Power), f(Fuel), g(Natural Gas), w(Drinking Water), c(Communication);

j = R(Residential), C(Commercial), I(Industrial), T(Transportation).

Our objective function is to find optimal α_{ij} to maximize total economic revenue $TER = \sum ER_i$, while the disruption of a certain infrastructure i. Economic revenue ER_i is the cumulative difference between income I_i and expenditures S_i in sector i over the model period [0, T]:

$$ER_i = \int_0^T (I_i - S_i)dt \tag{1}$$

Residential sector income is from wages, while income in the remaining sectors arises from output purchased by other sectors. Expenditures are divided into purchases of generic goods and services from other sectors, and purchase of infrastructure services such as electric power and fuel. Infrastructure service purchases are distinguished from generic commercial and industrial output because the specific technical factors influencing production and consumption are the focus of the model. No distinction is made between capital purchases (investment) and operating expenses in the commercial and industrial sectors. Purchasing rate for both generic goods and infrastructure output is a function of a normalized performance indicator X , which measures the current performance of each sector relative to its optimal value:

$$\underline{S} = f(\underline{X}) \tag{2}$$

A portion of the generic purchases made by each sector are assumed to be non-deferrable, in that if operational disruptions interfere with their timely execution they will not be reattempted later. Other purchases may be reattempted. The "function" $f(\ )$ is in general non-linear and path-dependent, and is specified by the dynamic model of the sector.

Figure 2 shows the sequence diagram to find optimal α_{Pj} when the power infrastructure has the loss of power generation capacity L_p. The required procedures to find the solutions are as follows:

- Step 1: Detect the loss of power generation capacity L_p due to the disruption or damage of power infrastructure. For example, L_p = 0.3 means that 30% of power generation capacity is lost.
- Step 2: Calculate available power production after the disruption, CI_P
- Step 3: Choose α_{pj} ($0 \leq \alpha_{Pj} \leq 1$), provide allocated power, $\alpha_{Pj} * D_{Pj}$ ($j = R, C, I, T$) to each economic Sector j. Here, $CI_P = \sum \alpha_{Pj} D_{Pj}$.
- Step 4: Calculate R_{pI}, R_{pC}, R_{pT} and LA from economic sector simulators. Relative available power R_{pj} is presented as a value from zero to one. One means the sector has enough power to fully satisfy corresponding power requests of other industry related infrastructures (e.g. petroleum and natural gas in our study). Its calculation includes the inventory, the own power generation and battery or alternative power sources of the economic sector. For example, R_{pI} = 0.8 means that the industry economic sector only has the power to satisfy 80% of industry power requests. R_{pI} = 0.8 is input to the corresponding infrastructure sub-system (petroleum and natural gas in our study). However, residential sector only provides the work forces to all infrastructures. It is also presented as a value from zero to one for available labors. Insufficient power supply to residential sector will decrease the labor availability not directly but indirectly with such as spending more time for commuting and house works.
- Step 5: Using given R_{pI}, R_{pC}, R_{pT} and LA, determine each availability of critical infrastructure materials/services CI_i ($I = f, g, w, c$) and distribute them to economic sector simulators with using each material/service market allocation algorithm.
- Step 6: Calculate Total economic Revenues, $TER = \sum ER_i$ ($i = R, C, I, T$)
- Step 7: Change α_{pj} and repeat step 3 to step 6 until finding the optimal TER.

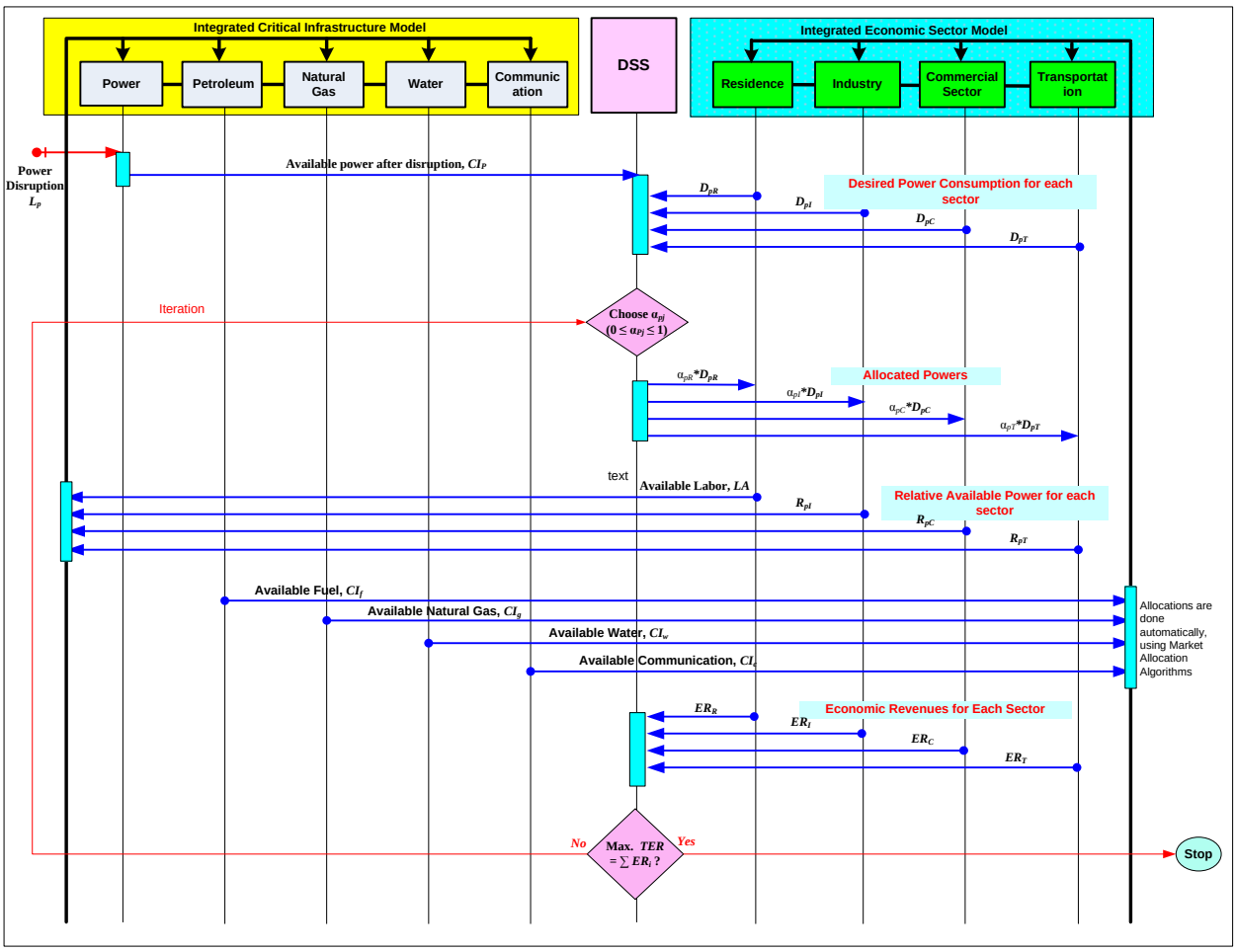

Figure 2: The sequence diagram of power disruption scenario

In this study, we have two allocation algorithms which include market allocation algorithm and simulation based non linear optimization algorithms. The market allocation algorithm uses supply curves specified for each infrastructure service provider, and demand curves defined for each sector, to determine a market-clearing price for each service. The supply curve for a particular infrastructure service may be compounded from different supply curves for different types of provider within each infrastructure service model. The supply curve for electric power, for example, is composed of supply curves for distinct generator classes (based on fuel type) as well as supply curves characterizing the willingness of connected regions to

export power. Demand curves are generally specified to be horizontal, so that infrastructure customers are price takers. The specification of inelastic demand reflects the assumption that customers will be unable to significantly change their process or technology over the time frame of the simulation. However, market allocation algorithm does not consider either markets of the other infrastructures materials or services, or national economical impacts. Without the any disruption of critical infrastructures, we assume that allocation of each infrastructure services/materials is determined by its market allocation algorithm. However, when we have a disruption of certain infrastructure and cause the shortage of service/materials of the disrupted infrastructure, the government or other federal institutions could intervene the market of the disrupted critical infrastructure, in order to satisfy or meet the global goal, which is finding the maximum national economic revenue during a certain satiation. In this study, the decision support system (DSS) finds the best strategy for allocation of insufficient materials/services of the disrupted infrastructure using simulation based non linear optimization algorithm.

As shown in Figure 2, our model divides to three major parts including integrated critical infrastructure model, decision support system (DSS), and integrated economic sector model. Integrated critical infrastructure model merged five individual critical infrastructure models which include power, petroleum, natural gas, drinking water and communication infrastructures. Each individual infrastructure model is built as the supply chain system of materials/services of an infrastructure using system dynamics modeling techniques. Each model is represented by an aggregate inventories and flows of materials/services of an infrastructure at an appropriate regional scale. For example, Figure 4 shows the power generation component of power infrastructure system dynamics model, which presents that state level aggregates of power demand drive the regional power generation rates with imports used to bring in cheaper power or

offset regional power shortfalls. In addition, each model is a stand-alone model prior to being merged into the integrated model. This allows individual model elements to be tested and utilized without the necessity or complexity of running the entire national interdependency model. Most of the demand for infrastructure services are not determined by other infrastructures, but by the economic sectors. The economic sector demand is aggregated at the regional level of for residential, commercial and industrial sectors of consumers. In this study, integrated economic sector demand model consists of four economic sector modules which are Residence, Industry, Commercial and Transportation. The role of these sector models is to define demands for the materials and services supplied by the basic infrastructures, capture the broader economic consequences of disruptions to those materials and services, and represent the interactions among those sectors to the extent that impaired performance in one sector, arising from infrastructure disruptions, may influence the economic activities and infrastructure demands in the other sectors. Finally, DSS includes the mechanism to find the allocation parameters using simulation based non linear search algorithm.

Figure 3 shows the IDEF∅ diagram for the high level view of the proposed interdependency simulation model of critical infrastructures and economic sectors. As mentioned earlier, more than 5000 variables and parameters have been considered in the entire integrated model in this research. Therefore, we have benefited from the hierarchical presentation and decomposition capability of IDEF∅. In the diagram, the rectangular box represents the functions and the arrows represent the information an object flow. Arrows entering on the left side of the box are the inputs to the function; arrows entering the top of the box are the control on the function; arrows entering the bottom of the box are the mechanisms that perform the function; and the arrows leaving the box on the right side are the outputs of the

function. Each function is associated with a unique ID number. Each function can be decomposed into detailed sub-functions as much as detail. The diagram shows the relationship among infrastructures and economic sectors, and also defines the variables which connect or interface among them.

Figure 4 depicts a Vensim system dynamics model of the power generation, where variables are functionally related with one another via either difference equations or differential equations behind the scene. For example, the function governing "Generation Serving load" in Figure 4 is shown below:

INTEGRAL(Bringing_Generation_on_Line[NERCRegion,GenTechnology]-Load_Serving_Generation_Becomming_Disconnected[NERCRegion,GenTechnology]-Load_Servin_Generation_Failing[NERCRegion,GenTechnology]-Switching_Load_Serving Generation to Idle[NERCRegion,GenTechnology])

Although the modeling discussed in this paper, including IDEF, system dynamics, and optimization models, are partial and have been slightly manipulated from the original ones for confidentiality, it does not affect the contents and goal of the proposed research.

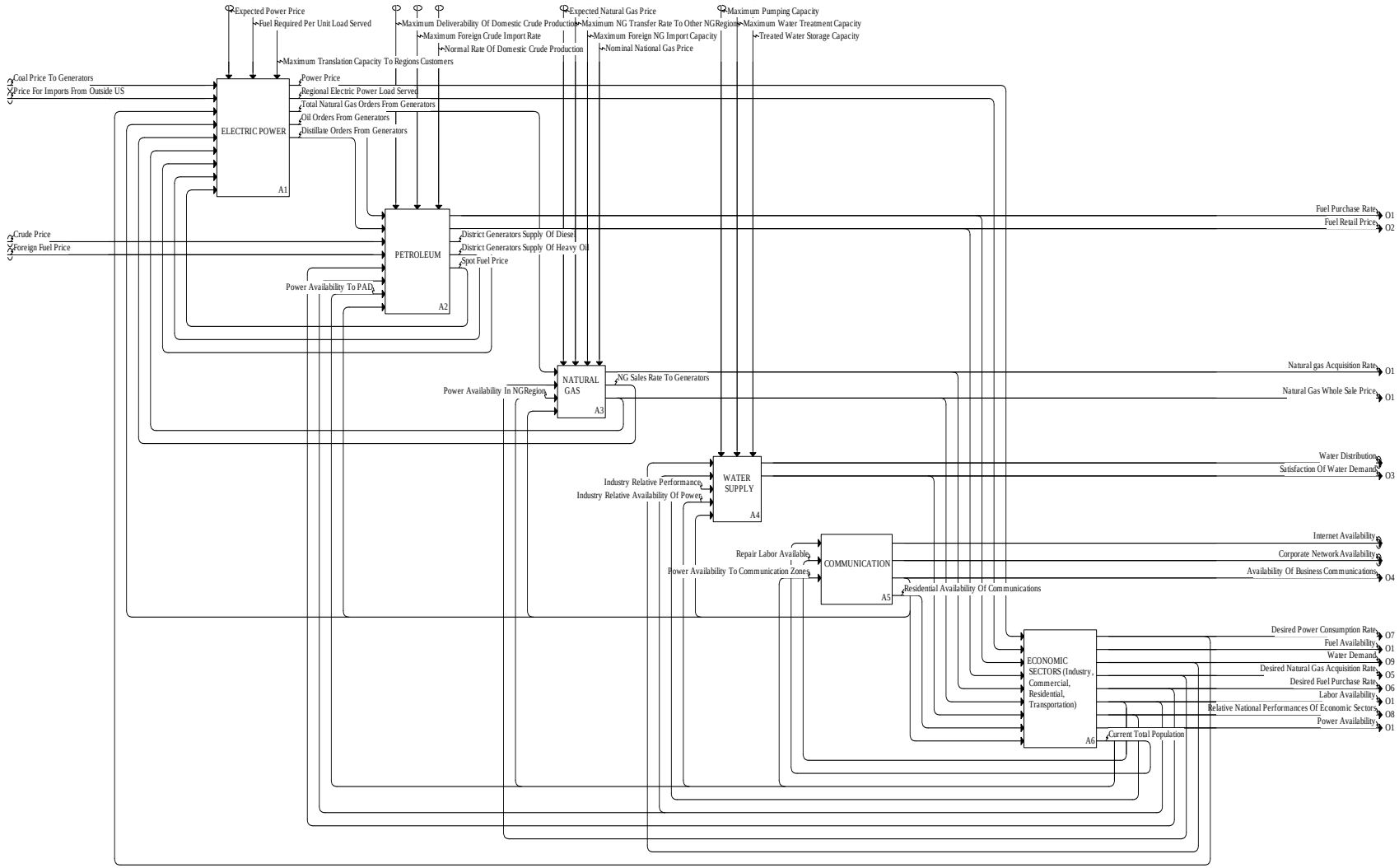

Figure 3: IDEF0 diagram of interdependency model of critical infrastructures

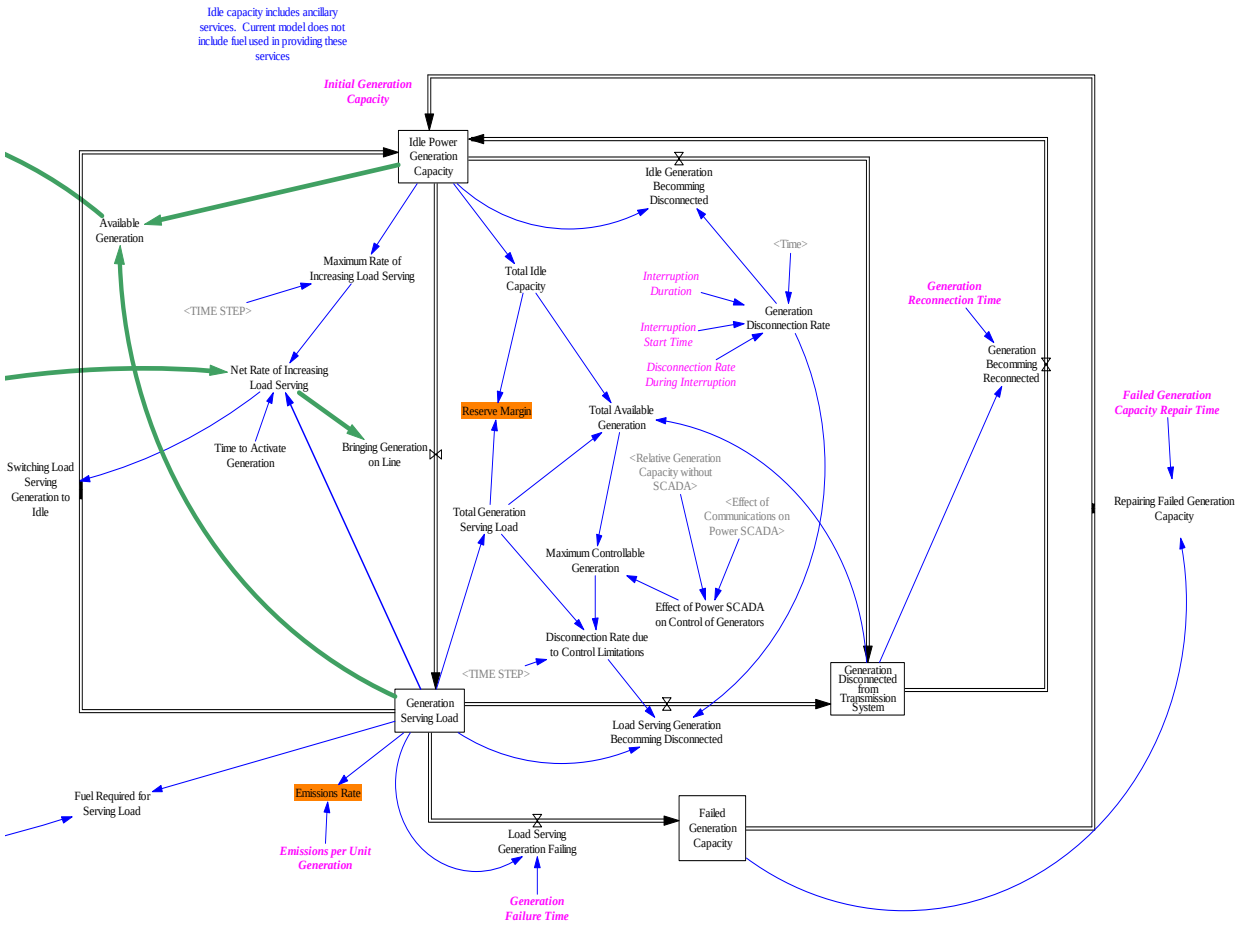

Figure 4: Power generation system dynamics model

4.2. Preliminary Experiments and Results

In this work, we have conducted a preliminary experiment based on three scenarios with the proposed models. Simulation start time is time *0* hour and all the parameters are initialized based on the historical data which are collected from both various government agencies and private industries. The time step Δt of system dynamics simulation is 0.25 hour, and the run length of the simulation is 108 hours. In Scenario 1, we run the base scenario without considering a disruption of any critical infrastructure. In Scenario 2, we have a power disruption

starting at time *60* hour and ending at time *108* hour. The loss of power generation capacity during the disruption is L_p = 0.4, which means 40% of power generation capacity is lost at time 60 hour. The allocation of power is determined by the decision support system using simulation based nonlinear optimization algorithm, and allocation of other infrastructure materials/services is determined by the market allocation of each critical infrastructure. In Scenario 3, we use the same conditions with Scenario 2 except that the market allocation algorithm of each critical infrastructure determined the allocation of each infrastructure materials/services. There is no intervention to markets of infrastructures materials/services by the government or other authorities.

Figure 5 depicts the comparison of the change of total revenue, $\Delta(\sum ER_i)$, over simulation run for three scenarios. The result reveals "Scenario 2" outperforms "Scenario 3" in terms of the change of total economic revenues. After the disruption occurred at time *60* hour, the change of total revenue, $\Delta(\sum ER_i)$ of Scenario 2 is always higher than that of Scenario 3. In addition, the cumulative total economic revenues of three scenarios during the disruption periods (from time 60 to time 108) are $1106M, $940M, and $603M, respectively. In terms of the cumulative total economic revenues during the disruption period, DSS (Scenario 2) outperforms the market algorithm of power (Scenario 3) by 15.6%. Therefore, based on the results of the experiment, the intervention of market of the critical infrastructure may be necessary in the case of disruptions or damages in order to minimize global economic impact.

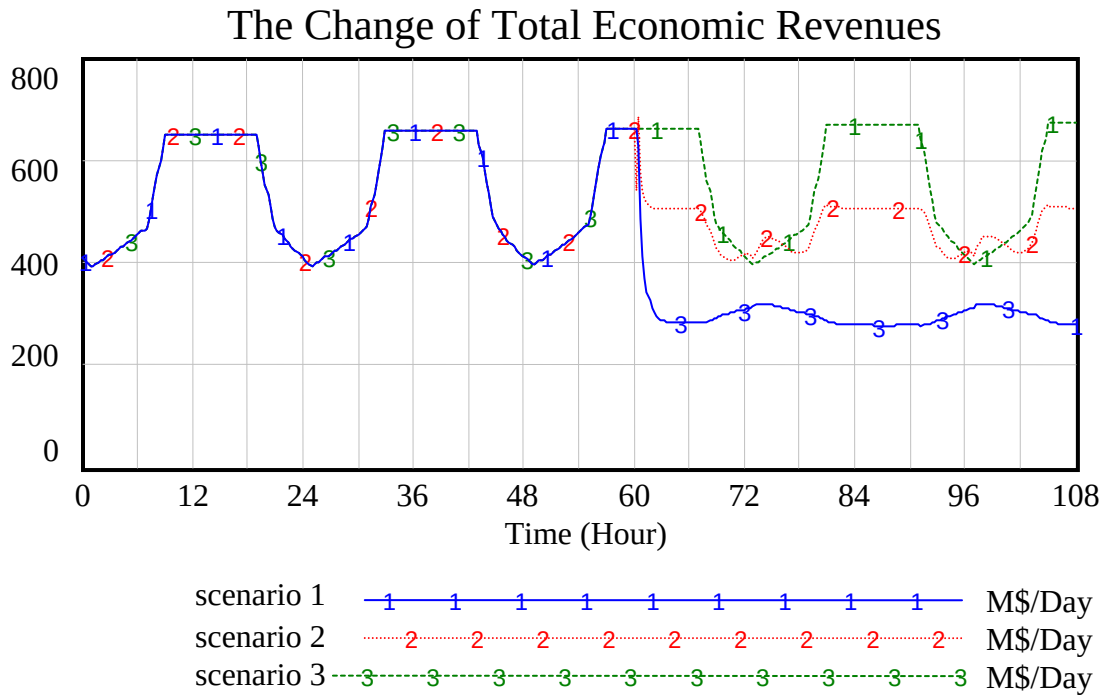

Figure 5: Comparison of results of scenarios

5. Conclusion and future works

The proposed interdependency simulation model of critical infrastructures determines (1) the availability of infrastructure services or materials to each of other infrastructures and to economic sectors for given specific scenarios of damage or disruption to a certain infrastructure, and (2) estimate the potential global economic effects of the given disruption with certain magnitude, extent, duration of disruptions on a infrastructure.

For the future work, each infrastructure model is very aggregated level so it might be good to be communicated with detailed simulation models of industrial manufacturing companies or communication and transportation network models. It will help decision-makers to test whether the policies from higher level is also feasible in lower level. In addition, it will be nice that the change of variables and parameters in lower level detailed simulator is updated to

the variables and parameters of higher level simulators in a real time fashion, in order to provide the accurate information to higher level decision-making process.

Acknowledgement

- By Theresa Brown

Product Disclaimer

Commercial software products are identified in this paper. These products were used for demonstrations purpose only. This does not imply approval or endorsement by both Sandia National Laboratory and NIST nor that these products are not necessarily the best available for the purpose.

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