Modeling and Simulating Critical Infrastructures and Their Interdependencies

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Abstract

Our national security, economic prosperity, and national well-being are dependent upon a set of highly interdependent critical infrastructures. Examples of these infrastructures include the national electrical grid, oil and natural gas systems, telecommunication and information networks, transportation networks, water systems, and banking and financial systems. Given the importance of their reliable and secure operations, understanding the behavior of these infrastructures – particularly when stressed or under attack – is crucial. Models and simulations can provide considerable insight into the complex nature of their behaviors and operational characteristics. These models and simulations must include interdependencies among infrastructures if they are to provide accurate representations of infrastructure characteristics and operations. A number of modeling and simulation approaches under development today directly address interdependencies and offer considerable insight into the operational and behavioral characteristics of critical infrastructures.

1. Introduction

Our national and economic security rest upon a foundation of highly interdependent critical infrastructures. These infrastructures are those "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters." [1] Infrastructures cover a large number of sectors, including the national electric power grid, oil and natural gas production, transportation, and distribution networks, telecommunications and information systems, water systems, transportation networks, the banking and finance industry, the chemical industry, agriculture and food systems, and public health networks. Understanding the operational characteristics of and providing a sufficient level of security for these infrastructures requires a "system-of-systems" perspective, given their interdependencies.

The sheer complexity, magnitude, and scope of the nation's critical infrastructures make modeling and simulation (M&S) important elements of any analysis effort. Individual infrastructures are complex in their own right, particular when considerations such as markets, government regulation, policy, legal regimes, and other socio-technical aspects must be included in analyses. However, infrastructures do not exist in isolation of one another – telecommunication networks require electricity, transportation networks often use sophisticated computerized control and information systems, the generation of electricity requires fuels, and so forth. To truly understand the operational characteristics of these infrastructures, their interdependencies must be integral to analyses. Omitting interdependencies will at best limit the validity of analyses, and at worse lead to bad or inappropriate policies and decisions during crises or severe infrastructure disruptions.

Infrastructure interdependencies are more than just a theoretical concern. Numerous recent policy documents recognize the importance of interdependencies, and in some cases, direct their study [2-5]. These documents underscore the clear recognition at senior policy levels of the importance of understanding interdependencies in national programs to protect critical infrastructures. While infrastructure service providers have vast experience responding to and mitigating day-to-day outages or minor disruptions, there is considerable concern that the nation prepare to respond to and recover from severe disruptions, perhaps resulting from a catastrophic terrorist attack or natural disaster. Given the lack of practical experience with massive infrastructure failures, M&S of infrastructure operations and characteristics should directly support national infrastructure protection initiatives. Interdependencies are similarly highlighted in numerous technical publications [6-9]. The underlying technical theme is that M&S of critical infrastructures must take a holistic, systems perspective and incorporate interdependencies.

In this paper, we will examine the complexity of the infrastructure interdependency problem, and review several M&S approaches that can be employed to analyze interdependencies. We begin with an overview of the interdependencies problem. We next discuss potential uses for interdependencies M&S, with a focus on improving critical infrastructure security. We follow with an overview of six different methodologies for analyzing interdependent infrastructures. We conclude with a brief discussion of some of the more significant challenges facing infrastructure M&S programs.

2. Interdependencies Overview

In this section, we will examine infrastructure interdependencies and their relevance to critical infrastructure M&S. Interdependencies give rise to numerous challenges that do not exist in single infrastructure models. A more detailed presentation of the material in this section can be found in [6].

An *interdependency* is a bidirectional relationship between infrastructures through which the state of each infrastructure is influenced by or correlated to the state of the other. As a simple example, the national electric power grid and natural gas network are interdependent – natural gas fuels many electrical generators, and elements of the natural gas infrastructure (e.g., gas conditioning plants, compressors, and computerized controls) require electricity to operate. A disturbance in the electrical system can cascade into the natural gas system, and loss of natural gas pressure can curtail the generation of electricity. Consequently, the states of these systems are mutually correlated. This simple case illustrates the importance of employing a systems perspective – an operational or security analysis of either infrastructure would be incomplete if it did not consider how the electric grid influences the state of the natural gas system and vice-versa.

There are four primary classes of interdependencies [10]:

- Physical Interdependency – two infrastructures are physically interdependent if the state of each depends upon the material output(s) of the other. Physical interdependencies arise from physical linkages or connections among elements of the infrastructures.
- Cyber Interdependency – an infrastructure has a cyber interdependency if its state depends on information transmitted through the information infrastructure. The computerization and automation of modern infrastructures and widespread use of supervisory control and data acquisition (SCADA) systems have led to pervasive cyber interdependencies.
- Geographic Interdependency – infrastructures are geographically interdependent if a local environmental event can create state changes in all of them. This implies close spatial proximity of elements of different infrastructures, such as collocated elements of different infrastructures in a common right-of-way.
- Logical Interdependency – two infrastructures are logically interdependent if the state of each depends upon the state of the other via some mechanism that is not a physical, cyber, or geographic connection. For example, various policy, legal, or regulatory regimes can give rise to logical linkage among two or more infrastructures.

Modeling interdependent infrastructures is a complex, multifaceted, multidisciplinary problem. Table 1 lists some of the factors arising from or associated with infrastructure interdependencies that complicate analyses. These factors drive one to a multidisciplinary approach, and may in fact preclude the development of a single, all-encompassing modeling methodology (“one size fits all”) for analyzing infrastructures. As described below, there are a variety of interdependencies M&S approaches, each of which addresses different factors listed in Table 1. The specific approach chosen may largely be determined by the issue(s) under consideration in the analysis.

3. Modeling and Simulation Roles

Modeling and simulation are components of ensuring the safe, reliable, and continuous operations of critical infrastructures. Given the national focus on homeland security since the September 11 terrorist attacks, security applications have taken on a new importance. M&S can play particularly important roles in understanding rare or extreme events for which there is relatively little practical experience. This section highlights some roles of infrastructure M&S that support homeland security programs and provide insights into extreme or rare events.

Table 1. Factors affecting interdependencies analyses

Factor	**Implications for Analyses**
Time Scales	Infrastructure dynamics vary from milliseconds (e.g., electrical grid disturbances) to decades (construction of major new facilities). Different infrastructures will have varying time scales of importance.
Geographic Scales	Specific scenarios and issues range from cities to national or international levels in scale. Scale affects the resolution and quantity of infrastructure and interdependency data required for models.
Cascading and Higher Order Effects	Disruptions in one infrastructure can ripple or cascade into other infrastructures, creating second and higher order disruptions.
Social / Psychological Elements	Infrastructures are socio-technical systems. Social networks and behavioral responses can influence infrastructure operations, such as the spread of an infectious disease and the response of the public health infrastructure.
Operational Procedures	Company-specific procedures influence the state of an infrastructure, such as responses to market fluctuations.
Business Policies	Specific corporate business policies affect the operations of the infrastructures.
Restoration and Recovery Procedures	Company-specific procedures influence the state of an infrastructure during a crisis or emergency, and may affect coordination among various infrastructure owners. Cross-infrastructure restoration/recovery procedures may not exist.
Government Regulatory, Legal, Policy Regimes	Government actions will influence operational behaviors as well as the response to and recovery from disasters or disruptions.
Stakeholder Concerns	Stakeholders have differing motivations and different sets of concerns that drive M&S requirements.

The *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* highlights M&S as a crosscutting initiative to increase the security of critical infrastructures [11]. The *Strategy* states that modeling, simulation, and analysis must be employed to “develop creative approaches and enable complex decision support, risk management, and resource investment activities to combat terrorism at home.” The *Strategy* specifically calls out six M&S activities:

- Integrate modeling, simulation, and analysis into national infrastructure and asset planning and decision support activities.
- Develop economic models of near- and long-term effects of terrorist attacks.
- Develop critical node/chokepoint and interdependency analysis capabilities.
- Model interdependencies among sectors with respect to conflicts between sector alert and warning procedures and actions.
- Conduct integrated risk modeling of cyber and physical threats, vulnerabilities, and consequences.
- Develop models to improve information integration.

Of note is the *Strategy’s* recognition of the importance of interdependencies.

We now examine in more detail specific applications of infrastructure and interdependencies M&S. First, determining the downstream consequences of the loss of elements in an infrastructure is a crucial aspect of interdependencies M&S. M&S can provide information about downstream consequences, such as which other infrastructures are affected (cascading and higher order effects), the geographic extent of infrastructure outages, and economic loses. There are instances where one is not concerned with the exact failure mechanism of specific infrastructure components, that is, whether the components failed due to a terrorist attack, aging, natural disaster, or some other cause. Rather, the focus lies on the ramifications of the failure. As an example, consider the simultaneous loss of a number of major electrical generation plants for some unspecified reason. What are the effects on the electrical grid itself, as well as the cascading effects into other infrastructures? What are the outage areas and durations in all affected infrastructures? What are the near-term and long-term economic costs arising from these outages? What are the human casualties?

What are the potential national and economic security implications? Properly cast, M&S can provide insights into these and other downstream consequences. Obtaining answers to these and other related issues would be crucial following a catastrophic infrastructure failure.

Second, M&S can provide insights into infrastructure operations during extreme and rare events, such as major natural disasters or catastrophic terrorism. A rare event could lead to the loss of multiple infrastructure components, potentially spread across large geographic regions. Modeling the effects of a rare or extreme event on infrastructure operations is in principle a straightforward process. By "knocking out" infrastructure assets in a model, one could simulate the effects of such an event and determine the associated downstream and cascading consequences. As an example, consider the approach of a major hurricane. By projecting its track over land, an analyst could determine those infrastructure elements at risk, such as electric power generation facilities and transmission lines. M&S could approximate the outage areas associated with the loss of those assets. Economic simulations could then be used to estimate the associated losses before the actual hurricane landfall, such as the productivity lost due to infrastructure disruptions. In a similar manner, other rare or extreme events can be simulated, thereby providing insight into the potential effects of the associated infrastructure disruptions.

It is important to note that such simulations will provide information on the downstream consequences associated with extreme events, but will rarely be predictive in the sense that they accurately portray the *exact* consequences associated with the event. Nonetheless, the insights gained from M&S can provide valuable inputs to recovery plans, reconstitution strategies, and mitigation plans. For some types of extreme events (particularly manmade events such as catastrophic terrorism), M&S insights may indicate policy gaps and help guide the policy development process. Given the rarity of these events, M&S may provide the only guidance available – the historical record may be too thin to be useful. Multiple simulations with stochastic variations could provide information on structural characteristics of these events – again, valuable information for strategy or policy development given the lack of historical data.

Third, M&S can provide additional insights into and assist with recovery from rare or extreme events with associated catastrophic infrastructure failures. As noted above, infrastructure service providers have extensive experience with relatively small scale and day-to-day outages. However, there is little experience with truly widespread, prolonged outages that have strategic significance to government, industry, and the general public [12]. From an interdependencies standpoint, there are few plans for response and recovery across multiple, affected infrastructures – most plans are specific to single infrastructures [13]. Plans could be analyzed and tested with M&S, thereby providing a measure of confidence in their viability and effectiveness during crises. Maintaining a systems perspective during recovery from catastrophic events is crucial, given that cascading effects could also be widespread.

Fourth, M&S is integral to infrastructure risk analyses. A comprehensive risk analysis has three primary components: (1) vulnerability assessments of specific infrastructure elements, assets, or sites; (2) downstream consequence analyses of the losses of infrastructure elements; and (3) threat assessments. We can cast risk of a system as:

$$R = P_A * (1 - P_E) * C,$$

where R is the system risk, P_A is the probability of attack, $(1 - P_E)$ is the probability of adversary success (and is composed of the probability of interrupting the attack and the probability of neutralizing the adversary), and C is the consequences of the attack. As discussed above, M&S can assist with the determination of downstream consequences of the loss of infrastructure assets. Furthermore, with an appropriate set of metrics, the downstream consequences can be used to determine or rank those nodes that are critical to infrastructure operations. A ranked list of key nodes or sites could drive further threat and vulnerability analyses as part of a systematic risk assessment process. Such a list would also be invaluable for resource allocation.

Fifth, M&S can be used for infrastructure policy development and analysis. Policies can be directly incorporated into some types of models, thus allowing simulations of the effects of those policies upon infrastructure behaviors and operations. For example, we have used dynamic simulations to examine the impacts of various security options on the economics of seaport operations [14]. Among the security options and policies we have simulated are the Customs-Trade Partnership Against Terrorism (CTPAT), the Container Security Initiative (CSI), Custom's 24 Hour Rule, container inspections, various types of container seals, and scanners. These types of analyses help determine the efficacy of policies, and potentially locate "leverage points" for the development of new policies. It may be possible to determine unanticipated effects of policies upon infrastructures, particularly if policies can "cascade" into other infrastructures. In a similar manner, new legal and regulatory requirements could be incorporated to determine their consequences, either desirable or unintended, upon infrastructures.

Sixth, M&S can be used to develop, test, and validate infrastructure protection strategies. Contingency plans and options for response, recovery, remediation, and reconstitution can be evaluated through simulation for their effectiveness and potential problems. Given that resources (funding, personnel, materiel) for protecting infrastructures are generally limited, different resource allocation strategies can be simulated and compared for effectiveness. Of particular interest is recovering from multiple, simultaneous infrastructure disruptions as quickly, effectively, and efficiently as possible. In certain instances, there may be constraints that dictate what can be reconstituted (e.g., availability of parts and repair crews) and in what order (e.g., restore electricity to the public health system first). M&S may be able to play a role in these types of constrained, strategy optimization problems.

Seventh, decision support systems and aids can be based upon M&S. Situational awareness tools, such as infrastructure monitoring and visualization, can provide advanced warning of potential problems or monitor developing crises. When linked to simulations, these tools may enable "what-if" exercises and analysis of downstream consequences of decisions. Interdependency M&S are particularly important, as decisions taken to support crisis operations in one infrastructure may affect operations in other infrastructures. A significant challenge associated with monitoring infrastructure status and operations is obtaining real-time operational data from the infrastructure owners. Information sharing faces substantial barriers that are described below.

Finally, exercises and training associated with critical infrastructure protection can incorporate M&S. The military has for decades employed simulations in its wargames and exercises. Similarly, exercises and training for personnel ranging from first responders to senior policy and decision makers in government and the private sector could be enhanced through simulations. Exercises often use scripted disaster scenarios, and the downstream consequences of participants' decisions and actions may be difficult to include in "real-time." Frequently, subject matter experts determine to the best of their abilities the consequences of decisions and actions during exercises. An infrastructure "flight simulator" could provide potentially richer and more detailed insight and feedback on decisions and actions to the exercise participants. These simulators could encompass extreme or rare events, for which there is little historical precedence or experience to guide actions. Additionally, simulations could be used to develop realistic training scenarios that accurately mirror the effects of disruptions. In short, M&S could enhance the fidelity, content, and value of exercises and training.

4. Modeling and Simulation Techniques

Models and simulations of individual infrastructures are rather well developed today – numerous products are available commercially that enable infrastructure owners to develop, operate, and manage their systems. However, M&S of multiple, interdependent infrastructures are immature by comparison. A number of different approaches to interdependent infrastructure M&S have emerged that address various factors listed in Table 1. This section provides a high-level description of several of these techniques.

We group interdependency models into six broad categories. These categories range from highly aggregated tools to very detailed, high resolution and fidelity models [15]. We are currently developing detailed interdependencies models and simulations in the first three classes described below at Sandia National Laboratories.

- Aggregate Supply and Demand Tools. This category of tools evaluates the total demand for infrastructure services in a region and the ability to supply those services. Multiple infrastructures can be linked by their demand for commodities or services provided by other infrastructures, and the ability of those infrastructures to satisfy demands. The ability of an infrastructure to meet its instantaneous or forecast demands can provide an indication of its health or early warning of potential problems (e.g., the inability to meet demand in multiple infrastructures). We have developed a prototype model that links the electrical grid, oil and natural gas systems, wireline telecommunications, and inland waterways in the Pacific Northwest. The prototype includes the ability to perform "what-if" analyses, so that the consequences and cascading effects of the loss of additional infrastructure assets can be determined in terms of aggregate supply and demand.
- Dynamic Simulations. We are employing dynamic simulations to examine infrastructures operations, the effects of disruptions, and the associated downstream consequences. The generation, distribution, and consumption of infrastructure commodities and services can be

viewed as flows and accumulations in the context of dynamic simulation. Interdependencies among infrastructures are readily incorporated into system dynamics models as flows of infrastructure commodities among multiple infrastructures. Moreover, dynamic simulations can examine the effects of policies, regulations, and laws upon infrastructure operations. We have developed detailed dynamic simulations of multiple, linked infrastructures, including energy (electricity, oil, natural gas), communications, transportation (waterways, highways, rail), emergency services, banking and finance, agriculture, water, shipping, and markets. We have constructed system dynamics models of infrastructures in California and the Pacific Northwest for analyses of the Northridge earthquake, the California energy crisis, and the impacts of security policies in the ports of Seattle and Portland.

- Agent-Based Models. Agent-based models have been used in a wide spectrum of interdependency and infrastructure analyses. Physical components of infrastructures can be readily modeled as agents, allowing analyses of the operational characteristics and physical states of infrastructures. Agents can also model decision and policy makers involved with infrastructure operations, markets, and consumers (such as firms and households). We have developed agent-based models of supply chains (manufacturers, distributors, households, labor sectors), telecommunications (wireline, wireless, satellite), electric power, transportation, banking, and governmental policies. Using these models, we have examined the consequences of the losses of infrastructure services upon manufacturing supply chains. These microeconomic analyses have enabled us to examine how infrastructure disruptions affect firms, their relative ability to compete during disruptions, and the effects of infrastructure-related policies on the ability of firms to survive disruptions.
- Physics-Based Models. Physical aspects of infrastructures can be analyzed with standard engineering techniques. For example, power flow and stability analyses can be performed on electric power grids, and hydraulic analyses can be used with pipeline systems. These models can provide highly detailed information, down to the individual component level, on the operational state of the infrastructures. These techniques have been applied to interdependent energy infrastructures, examining issues such as outage areas associated with single and multiple contingencies [16].
- Population Mobility Models. This class of model examines the movement of entities through urban regions. Entities interact with one another, generating and consuming infrastructure commodities in the process. For example, the entities may be people following their daily routines in a city. By generating and simulating these routines, a population mobility model can determine the use of multimodal transportation assets and assist with urban transportation or evacuation planning. An important characteristic of these models is that they develop detailed insights into social networks, which can be critical for certain types of studies such as epidemiology. Population mobility models have been used for extremely high resolution and fidelity urban interdependencies studies of multimodal transportation, electrical power girds (including electrical markets), wireless telecommunications, and epidemiology [17].
- Leontief Input-Output Models. Leontief's model of economic flows can be applied to infrastructure studies. The basic model provides a linear, aggregated, time-independent analysis of the generation, flow, and consumption of various commodities among infrastructure sectors. This model has been extended to include nonlinearities and time dependencies, and applied to examining the spreading of risk among interdependent infrastructures [18].

5. Future Challenges

A number of significant challenges face developers of interdependencies models and simulations. These hurdles and potential solutions are not just technical; some may require changes in laws or regulations. We will discuss several of the key challenges in this section.

Obtaining the requisite data to enable the models to accurately represent infrastructures presents arguable the biggest hurdle. First, there are several crucial forms of data to which a modeler must have access. The infrastructure topology – how the infrastructure is built and interconnected with other infrastructures – is clearly essential. Key data also include the operational, emergency, and other procedures used by infrastructure owners that influence infrastructure states during normal or crisis operations. Government and corporate policies also influence operations and comprise an element of data.

The modeler must be cognizant of these and other data types and, importantly, have access to the data.

However, gaining access to data is not necessarily easy. The private sector owns and operates the vast majority of infrastructures and consequently controls access to substantial quantities of crucial information, much of which is proprietary. There are significant barriers to sharing information between the private sector and government. These barriers include concerns about release of information under the Freedom of Information Act (FOIA), antitrust laws, confidentiality and privacy issues, liability issues, access to classified national security information, and reservations about sharing information with the law enforcement community [19]. Although some of the barriers are currently being addressed by legislation, such as FOIA [20-21], obtaining access to sufficiently detailed and high quality data remains a crucial issue to the development of interdependencies M&S.

Data must also be available in a timely fashion, particularly for certain applications. Real-time monitoring of infrastructures requires real-time access to data across multiple infrastructures. Even if access to such information is granted, ingesting, verifying, warehousing and using the data in real-time is a nontrivial problem. Moreover, data necessary for non-real-time applications are perishable and must be updated and verified regularly. For example, physical infrastructure topologies are not static – telecommunications and information service providers regularly augment their networks with new lines and equipment, new roads and highways may be added to a region, airlines may modify their flight schedules and routes, and so forth.

For certain stakeholder issues, it may be desirable to integrate multiple models or different classes of models together in a "co-simulation." There are substantial technical issues to creating a co-simulation, such as embedded (and often conflicting) assumptions in the models, different time steps, varying spatial scales, and different data requirements. Comprehensive simulation frameworks that couple disparate models to address the spectrum of stakeholder concerns are only beginning to emerge, and will take time to mature.

Verification and validation are fundamentally important to M&S development. We have used several techniques with our models and simulations, including comparing model outputs to historical data, using widely accepted models as benchmarks for testing new models, and obtaining feedback from experts in seminar settings. One must take care when comparing model outputs to historical data, as infrastructure technologies change with time. It is important that the model accurately reflect the infrastructure technology in use during the timeframe of the comparison. For example, the information infrastructure of the United States has advanced tremendously over the past decade – a fact which must be taken into account in any comparisons to historical data more than a few years old.

Similarly, models and simulations must keep abreast of changes in infrastructure technology. Models that accurately reflect the state of technology today could be outdated in a few years. This problem may be particularly challenging for cyber interdependencies, given the explosive growth in information technology.

Finally, metrics that accurately represent the state of infrastructures present another major challenge. There are no satisfactory metrics today that would enable:

- comparisons of mitigation, response, recovery, reconstitution, and restoration strategies;
- comparisons of the "criticality" of nodes and links;
- determination of appropriate investment strategies to increase security; and
- evaluation of the relative effectiveness of security measures and policies.

Development of a comprehensive and widely accepted set of metrics should be a component of the national critical infrastructure protection program.

6. Conclusions

The multidisciplinary science of interdependent infrastructures is relatively immature today. Developing a deeper understanding of interdependencies and their implications for infrastructure security will require a comprehensive R&D agenda that encompasses multiple disciplines ranging from engineering and complexity science to sociology, policy research and political science. Modeling and simulation will undoubtedly play a key role in the development of this science.

Modeling and simulating infrastructure interdependencies are far from easy exercises. Developing appropriate tools is technically challenging, with numerous hurdles to overcome. However, a number of techniques have been successfully applied to the analysis of multiple, interconnected infrastructures. Given the importance of preventing catastrophic infrastructure failures and mitigating those that might appear, the current research momentum in this field must be maintained.

7. References

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