Chapter 23

THE ISE METAMODEL FOR CRITICAL INFRASTRUCTURES

Felix Flentge and Uwe Beyer

Abstract The implementation-service-effect (ISE) metamodel is a general framework for modeling critical infrastructures that can integrate several different perspectives. The metamodel has a technical basis and also provides the abstractions needed for risk assessment and management of critical infrastructures in complex environments. ISE supports an iterative modeling approach that continuously refines models based on new information. By focusing on the services provided by critical infrastructures, the approach bridges the gap between the business and engineering views of critical infrastructures. The technical realization of services is described in the implementation layer of ISE; the effects of the successful (or unsuccessful) delivery of services are described in the effect layer. A sound mathematical foundation provides the basis for analyses ranging from topological evaluations of dependency structures to statistical analyses of simulation results obtained using agent-based models.

Keywords: Infrastructure modeling, interdependencies, ISE metamodel

1. Introduction

Modern societies rely to a large extent on the undisturbed availability of services provided by critical infrastructures. The massive use of information and communications technology, and deregulation and globalization trends have led to the emergence of new dependencies between infrastructures while aggravating existing dependencies. The increased complexity of critical infrastructures as a whole raises security issues that cannot be addressed appropriately using a narrow view of a single infrastructure. Some of the problems include cascading, escalating and common cause infrastructure failures [11], which require new approaches for risk assessment and management. Models must be constructed to describe complex dependencies and support detailed analysis. Furthermore,

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simulation methods must be developed to understand the dynamic behavior of critical infrastructures and evaluate risk management solutions.

Several approaches have been proposed for modeling and simulating dependencies between infrastructures [1, 2, 4, 13–15]. Most approaches focus on dependencies in only a small portion of the overall infrastructure, e.g., Aspen-EE [3], which examines the economic aspects of the electric power infrastructure. Wolthusen [16] uses geographic information systems (GISs) to identify and analyze geographical dependencies. Hopkinson, *et al.* [8] employ simulations to investigate interdependencies between the telecommunications and electric power infrastructures. However, the modeling and simulation of complex dependencies between infrastructures is still in its infancy. While several commercial simulators are available for analyzing single infrastructures, there is a lack of systems that can handle multiple infrastructures or address the technical and human aspects.

The implementation-service-effect (ISE) metamodel described in this paper is a general modeling framework that combines viewpoints from different sectors and professions. It provides a strong technical basis as well as abstractions needed for modeling and analyzing risk in critical infrastructures.

2. Critical Infrastructure Modeling

Interdependencies between critical infrastructures are due to many nonlinear factors that can vary dramatically from case to case. Furthermore, there are several levels of possible interactions among the components of large, complex infrastructure networks. Reliable models for analysis and simulation can only be developed by taking real data into consideration. This leads to a "chicken and egg problem." Data availability is a limiting factor [9]. Infrastructure providers are generally unwilling to release technical data before risks have been identified (if at all); but risk analysis cannot proceed without appropriate data. The ISE model of critical infrastructures offers a solution by providing an iterative modeling approach that starts with an abstract model and publicly-available data. General problems can be discovered using this data, which helps refine the initial model. The iterative approach progressively refines the new model at each step based on new data.

Another problem encountered when modeling complex interrelationships is the "particular answers dilemma." This problem arises because system behavior is often dependent on low-level technical details. A small change in a technical detail can have a significant impact on overall system behavior. However, it is difficult – if not impossible – to model a system down to its lowest level. In fact, some of the data needed for system modeling may not even be observable. One way to deal with this problem is to develop taxonomies of dependencies and develop general strategies for dealing with classes of dependencies. A modeling approach with a sound mathematical background can facilitate the identification and description of dependency classes. This problem is closely related to that of choosing the right abstraction level. If the level of abstraction is too high, trivial results are obtained. If the level is too low, too much data is involved and it may not be possible to identify the underlying structures.

The analysis that follows the modeling process is also somewhat problematic. Few, if any, general methods exist for analyzing complex infrastructures and their dependencies (most methods only deal with abstract networks). The lack of common modeling and analysis methodologies also makes it difficult to evaluate models and compare results. The ISE metamodel provides a sound mathematical foundation to build a variety of models with the same underlying structure. Systems of dependent critical infrastructures can be described in a well-defined manner and analysis can proceed using well-established methods.

Critical infrastructure protection is a problem that straddles several disciplines. According to Dunn [6], critical infrastructure protection involves at least four different perspectives: a system-level technical perspective, a business perspective, a law-enforcement perspective and a national security perspective. Since it is difficult to reconcile different views, most models only focus on a single perspective. The ISE model, on the other hand, integrates the technical and business perspectives while accommodating the national security perspective.

3. Implementation-Service-Effect Metamodel

Infrastructure dependencies must be modeled at the right level of abstraction to facilitate analysis. The ISE metamodel supports an iterative approach that starts with limited data and an abstract model, which is refined in a step-by-step manner to permit more accurate analysis. The approach also facilitates the modeling of a critical infrastructure from different viewpoints and the integration of the different viewpoints to produce a single coherent model. A critical infrastructure may be modeled from a business perspective, which focuses on business continuity, risk analysis and risk mitigation. Alternatively, one may construct a detailed physical model, which provides insight into the critical infrastructure at the engineering level and helps determine weak points in the design.

The gap between a business model and a technological model is bridged by introducing a service layer. This layer models the services produced by infrastructures along with their mutual dependencies. Since all services are directly or indirectly based on some technical implementation, a natural mapping exists from the implementation layer to the service layer. On the other hand, because services are either products sold by private companies or are at least guaranteed by public sector (or quasi public sector) providers, the delivery of services and the quality of delivery have an effect on the service provider's business and overall approval. Thus, a natural mapping exists from services to effects. The focus on services guarantees that relevant functions and effects of real systems are taken into account, leading to a practical model.

An ISE model comprises several ISE submodels that describe different infrastructures or different components. The submodels contain three types of elements: implementation elements, services and effect factors. A complete ISE model is created by combining several submodels, describing their dependencies

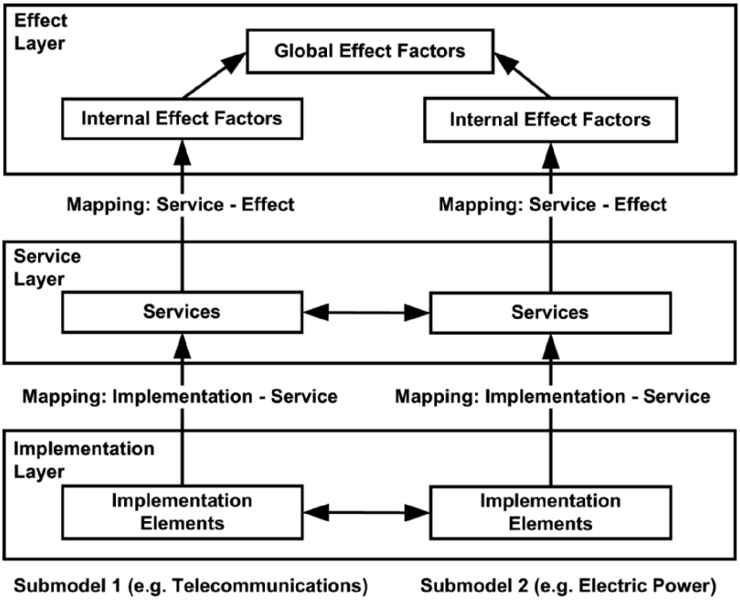

Figure 1. Structure of an ISE model with two submodels.

(within and across submodels) and adding global effect factors. The resulting model has three layers: implementation layer, service layer and effect layer. The relationships between these layers are described by two mappings, the implementation-service mapping and the service-effect mapping. The general structure of an ISE model with two submodels is shown in Figure 1. Note that dependencies between elements of different submodels can only appear within the same layer. Dependencies in one submodel always appear within the same layer or in a top-down manner; therefore, they can be modeled as directed graphs.

The following sections describe each layer in detail. A formalism that facilitates the analysis of ISE models is also introduced.

3.1 Service Layer

The purpose of critical infrastructures, regardless of their ownership, is to provide services in a reliable manner. These services are delivered to the end-customer, to another critical infrastructure (public services) or to some other part of the same infrastructure (internal services). Services can be viewed at various levels of abstraction. One approach is to describe services in the form of trees. For example, in the electric power infrastructure, the abstract service "delivery of electricity to the end-consumer" could be subdivided into "generation of electricity," "transmission of electricity from the generation level

Table 1. Infrastructure services.

Telecommunications	**Electric Power**
Fixed Line Telephony	Generation
GSM	Transmission
SMS	Distribution
DSL	Maintenance
GPRS	Control

to the distribution level," and "delivery of electricity from the distribution level to the end-consumer."

The reliability of service delivery depends on various aspects of a critical infrastructure (physical equipment, organization, human resources, etc.) and to some extent on the reliability of other services. For example, the delivery of communications services depends on the availability of electricity. An entire network of services is exchanged between different infrastructures and end-consumers. Therefore, it is extremely important to ensure the reliable delivery of services. Of course, protecting physical equipment and securing information technology assets are important, but critical infrastructure protection encompasses much more than just these tasks:

> "More often than not, the actual objects of protection interests are not static infrastructures, but rather the services, the physical and electronic (information) flows, their role and function for society, and especially the core values that are delivered by the infrastructures. This is a far more abstract level of understanding of essential assets, with a substantial impact on how we should aim to protect them [6]."

The service layer is the central layer of an ISE model. In the case of private companies, services are products that are usually accompanied by service level agreements (SLAs). In the case of (quasi) governmental infrastructure providers, there may be SLAs as well as other kinds of regulations. Therefore, services should be easily identifiable as they provide a good starting point for modeling. Internal services usually can be identified by examining the internal structure and organization of enterprises. Table 1 lists examples of services in the telecommunications and electric power infrastructures.

Of course, services may be considered at different levels of abstraction. For example, in one case, the delivery of electricity might be modeled as a service; in another, the delivery of electricity to a specific customer. In general, what should be considered as a single service depends on the purpose of the model. If the focus is on dependencies between infrastructures, one would most certainly distinguish between services delivered to other infrastructures and services delivered to the general public.

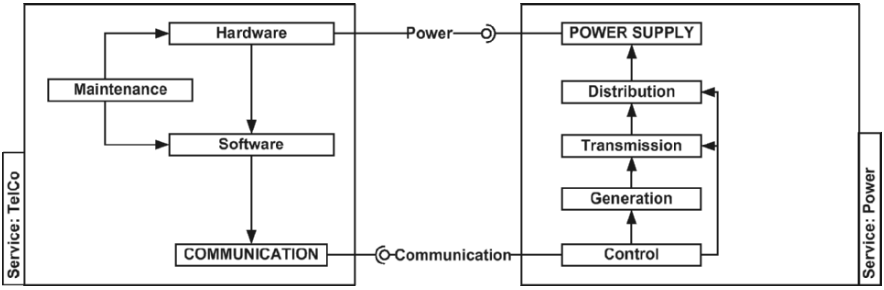

Figure 2. Service layers.

Formally, the service layer S of an ISE model consists of internal services IS^i and public services PS^i of all submodels i:

$$\begin{aligned} S &= \bigcup_{i=1,\ldots,n} \left(IS^i \cup PS^i\right) \\ IS^i &= IS^i_1, \ldots, IS^i_k \\ PS^i &= PS^i_1, \ldots, PS^i_l \end{aligned}$$

The dependencies between services in an ISE model are described by a service dependency graph $SDG = (S, DS)$ with $DS \subseteq S \times S$. The vertices of a service dependency graph are services and the edges are dependencies between services. Edges are directed according to the direction of influence: an edge (a, b) exists when b is dependent on a.

The ISE model requires certain constraints to be satisfied by dependencies. Using graph theoretic notation, we define the set of predecessors of a vertex a in a graph $G = (V, E)$ as:

$$N^-_G(a) = \{a_i | \, (a_i, a) \in E\}$$

The constraints on a service dependency graph are formally defined as:

$$N^-_{SDG}(a) \subseteq IS^k \cup \bigcup_{i=1,\ldots,n} PS^i \quad \text{for all } a \in IS^k \cup PS^k$$

Note that a service of a submodel k cannot be dependent on the internal services of other submodels.

Figure 2 shows an example of a simple service topology with dependencies between the telecommunications and electric power infrastructures. The vertices of the service dependency graph represent public services (all capitals) and internal services (upper and lower case). The edges describe how services are dependent on other services (i.e., “subservices” that guarantee the proper operation of dependent services). Interdependencies exist between infrastructures when there are mutual exchanges of services between the infrastructures.

3.2 Implementation Layer

Services are realized by technical or organizational measures in the implementation layer. This is done by offering "implementation elements" to the service layer. The implementation layer is very heterogeneous because it encapsulates individual details of infrastructures. It includes physical equipment as well as all that is needed to provide services (e.g., human operators, organizational measures and procedures). Often, three elements are distinguished as in the U.S. National Infrastructure Protection Plan of 2006 [5]: physical (physical components that produce and deliver infrastructure services), cyber (hardware, software and information used to monitor and control physical components), and human (people who monitor and control the infrastructure and service delivery).

Table 2. Implementation elements.

Telecommunications	**Electric Power**
Base Stations	Generators
Base Station Controllers	Transmission Lines
Network Operation Control Centers	Distribution Lines
Operators	Consumers
Communication Links	Control Centers

Table 2 provides examples of items included in the implementation layer. There is almost no limit to the level of detail. However, if one starts with the service layer, it is usually sufficient to model the implementation elements at the subsystem level and not at the component level.

The implementation layer comprises the implementation elements IE^i of all submodels i:

$$\begin{aligned} I &= \bigcup_{i=1,\ldots,n} IE^i \\ IE^i &= IE^i_1, \ldots, IE^i_j \end{aligned}$$

Once again, dependencies are modeled as a directed graph, the implementation dependency graph $IDG = (I, DI)$ with $DI \subseteq I \times I$. There are no special constraints on this graph; each implementation element may depend on any other implementation element. However, dependencies between submodels in this layer usually have counterparts in the service layer.

Figure 3 shows the implementation layer of an electric power infrastructure and a supporting telecommunications infrastructure along with the dependencies between them. The implementation layer of the electric power infrastructure includes a control center, substation, generators, transmission lines and distribution lines. The telecommunications infrastructure is modeled more abstractly with human resources, four communication units and a communication

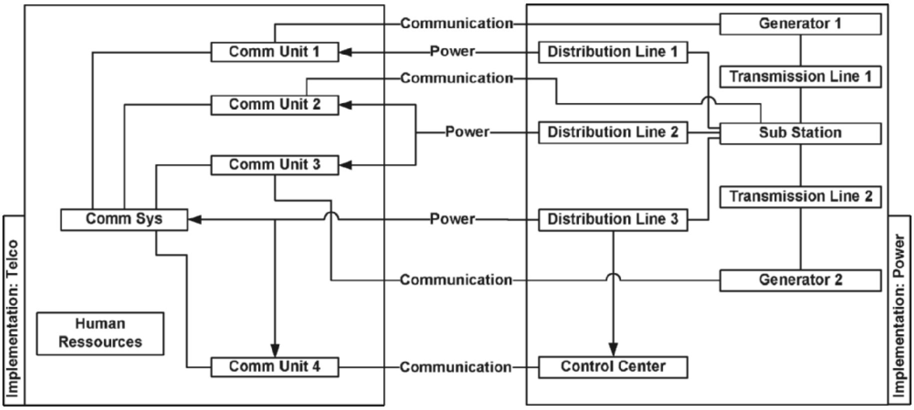

Figure 3. Implementation layer.

system that connects the communication units. The telecommunications equipment is powered by distribution lines. In turn, the communication system and the communication units enable communications between the control center and other system components (generators, substation). The communications are necessary to monitor and control the generation and transmission of electricity.

3.3 Effect Layer

The effect layer, which lies on top of the service layer, describes the effects of the successful or unsuccessful delivery of services. Effects may be expressed in terms of revenues or profits/losses, risk, affected people, public opinion, etc. Internal effect factors describe effects specific to a submodel. Global effect factors combine the internal effect factors of submodels to describe the effects of multiple infrastructures. Formally, the effect layer E of an ISE model consists of the global effect factors EF^* and the effect factors EF^i of all submodels i:

$$\begin{aligned} E &= EF^* \cup \bigcup_{i=1,\ldots,n} EF^i \\ EF^* &= EF^*_1, \ldots, EF^*_l \\ EF^i &= EF^i_1, \ldots, EF^i_k \end{aligned}$$

The dependencies between effect factors are given by the effect dependency graph $EDG = (E, DE)$ with $DE \subseteq E \times E$. The only constraint on the effect dependency graph is:

$$N^-_{EDG}(a) \subseteq EF^k \quad \text{for all } a \in EF^k$$

i.e., internal effect factors cannot depend on internal effect factors of other infrastructures or on global effect factors.

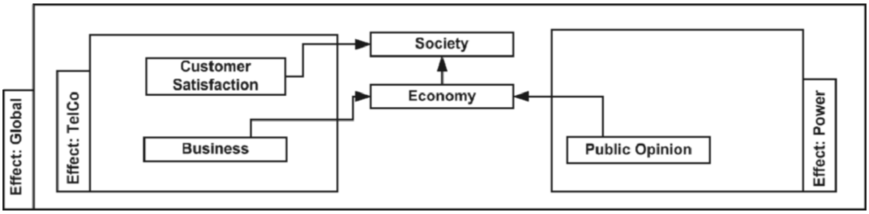

Figure 4. Effect layer based on services.

The effect layer is important from the business point of view, especially for performing business impact analyses and risk assessments. Furthermore, existing approaches for modeling risk in the context of critical infrastructures (e.g., [12]) may be integrated. Figure 4 shows a simple example of an effect layer.

3.4 Implementation-Service Dependencies

Services are based on the implementation layer: several implementation elements have to interoperate correctly to provide a service. These dependencies are described by the implementation service dependency graph $ISDG = (I \cup S, DIS)$ with $DIS \subseteq I \times S$. Edges in $ISDG$ always originate from an implementation element to a service, i.e., only dependencies between the two layers, not within each layer, are considered in the graph. An additional constraint is that the dependencies have to be in the same submodel k:

$$N^{-}_{ISDG}(a) \subseteq IE^k \quad \text{for all } a \in IS^k \cup PS^k$$

Figure 5 shows examples of vertical dependencies in a telecommunications infrastructure and an electric power infrastructure. The service Hardware in the telecommunications service layer is dependent on technical equipment in the implementation layer. Also, Maintenance is dependent on Human Resources. The electric power infrastructure has more dependencies. The service Control is dependent on the implementation element Control Center that may include technical equipment along with human operators. The services Generation, Transmission and Distribution are dependent on their specific elements in the implementation layer.

3.5 Service-Effect Dependencies

Internal effects are based on the states of the services of the respective infrastructures. These dependencies are described by the service effect dependency graph $SEDG = (S \cup E', DSE)$ with $DSE \subseteq S \times E'$ and $E' = E \setminus E^*$, i.e., only internal effect factors are considered. Once again, dependencies exist between the two involved layers, not within the layers. The following condition ensures

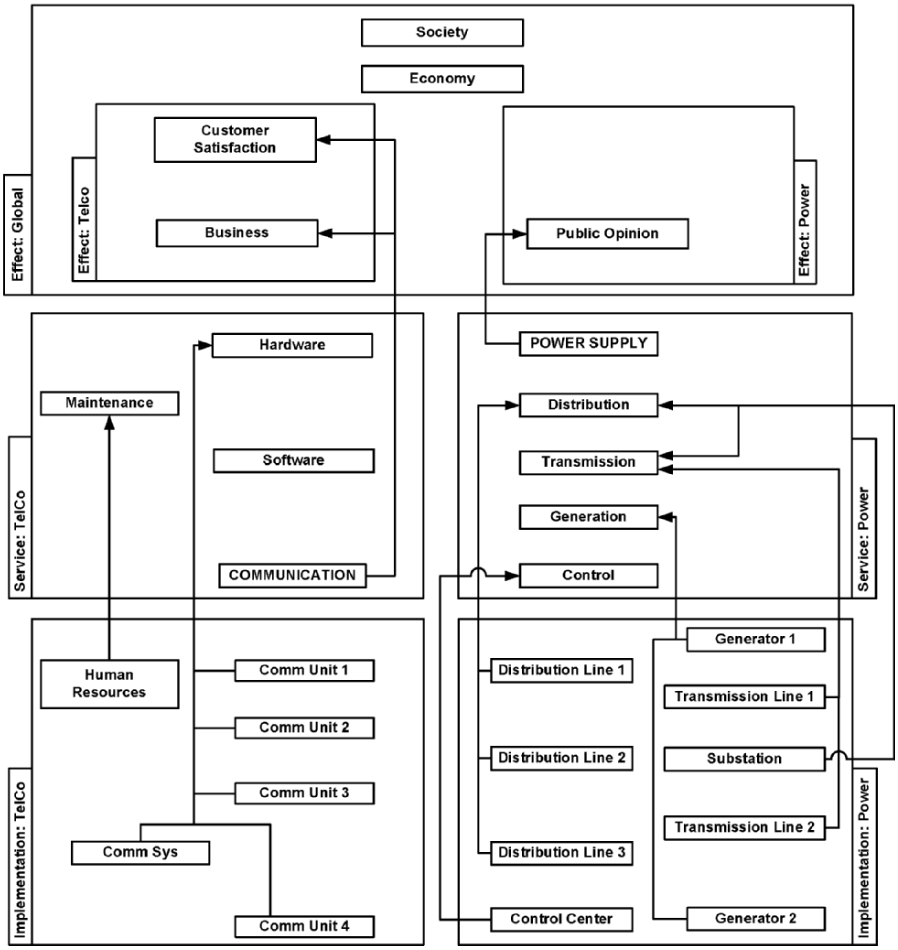

Figure 5. Vertical dependencies between submodels.

that dependencies appear only within the same submodel k:

$$N^{-}_{SEDG}(a) \subseteq PS^k \cup IS^k \quad \text{for all } a \in EF^k$$

Figure 5 shows effects that are dependent on services in the telecommunications and electric power infrastructures. Note that different effects can be based on the same service, e.g., communication service influences company revenue as well as consumer satisfaction.

4. Iterative Modeling and Analysis

The ISE metamodel supports an iterative modeling approach: the process starts with an abstract topological model of the service layer, which is iteratively refined by including additional layers and/or submodels. The elements in each layer and the associated dependencies are described in more detail in each refinement step. We distinguish between four principal types of models based on their elements and dependencies: topological models, Boolean models, numerical models and simulation models. Different models may be combined; moreover, based on the nature of the elements and dependencies in a specific model, it is possible to perform different types of analyses.

4.1 Topological Models

A topological model only uses information contained in the five ISE model graphs. For example, the service dependency graph and the implementation dependency graph may be analyzed for cycles, which could indicate possible problems in infrastructure recovery after a disruption. Also, the implementation service dependency graph and the service effect dependency graph can be used to express the relationships between paths in one layer and paths in another layer. For example, a path in the service layer should have a counterpart in the implementation layer and vice versa:

$$\text{Let } (i_1, s_1), (i_2, s_2) \in ISDG:$$
$$\text{Path } (i_1, \ldots, i_2) \text{ exists in } IDG \quad \Leftrightarrow \quad \text{Path } (s_1, \ldots, s_2) \text{ exists in } SDG$$

Statements of this kind can be used to check the consistency of a model and to relate dependencies in one layer to elements and dependencies in another layer. Moreover, taxonomies of dependencies can be constructed, general structures can be detected and strategies for dealing with problematic dependencies can be devised.

4.2 Boolean Models

Topological models indicate where possible problems may arise; however, topological analyses can only make very limited statements about the nature of these problems. For example, in the implementation layer in Figure 3, the failure of Generator 1 may not have severe consequences if Generator 2 is working and produces enough electricity to supply all the loads connected to the distribution lines. Such a situation is modeled more easily using a Boolean model. Each element has a Boolean value, which indicates whether the element is working or not. A Boolean expression is used to calculate the Boolean value of an element based on the values of other elements. Since cycles may exist in the dependency structure, a notion of time must be introduced. In particular, the value of an element at time t is calculated based on values at time $t-1$. For example, the Boolean value of a substation at time t, b_t(substation), depends on the Boolean values of two transmission lines at time $t-1$:

$$b_t(\text{substation}) = b_{t-1}(\text{transmission line 1}) \text{ OR } b_{t-1}(\text{transmission line 2})$$

Boolean models support "what-if" analyses. Different initial settings can be assumed and the effects of failures can be investigated. Boolean expressions for various elements can be adjusted to account for different conditions. For example, if one generator cannot produce enough electricity for the distribution system, the OR operator in the expression above could be changed to an AND. However, Boolean models cannot handle time-based effects such as the slow degradation or recovery of a service. More complex, numerical models are required for these and other situations.

4.3 Numerical Models

A wide range of numerical models have been proposed. The simplest models extend the Boolean model by replacing Boolean values with real numbers and Boolean expressions with mathematical functions. For example, numerical values could be assigned to service inoperability levels as in Leontief-based models [7, 10]. More complex numerical models use vectors to specify properties of elements (e.g., quality of service (QoS) parameters). Some models employ differential equations to model temporal aspects. Others use random variables or fuzzy variables to account for objective or subjective uncertainty, respectively.

4.4 Simulation Models

When conducting a simulation, each infrastructure element can be modeled as an autonomous agent with specific attributes and behavior. The behavior of an agent depends on its own state as well as on the states of other agents that influence it; agents influence other agents in the direction of the dependencies. Generally, the complexity of a simulation model decreases from the implementation layer to the effect layer. Implementation elements may be modeled and simulated using existing tools. Usually, services are described by real number values (for availability, quality of service, etc.); effects (e.g., profits/losses, revenues, risk, etc.) are also described by real number values. Time-based simulations may be conducted with different initial values and for different scenarios (e.g., changes in service consumption or failures of certain elements). The systematic manipulation of factors in the implementation layer allows the sampling of sets of service qualities at the service layer. Based on these values, the corresponding effect factors may be evaluated. Producing sample sets of possible effects as a function of infrastructure elements facilitates the application of a range of statistical analysis methods.

5. Conclusions

The ISE metamodel is a novel approach for modeling critical infrastructures along with their dependencies and interdependencies. ISE supports an iterative modeling approach that starts with an abstract model and publicly-available data, and continuously refines the model at each iteration based on new information; this addresses problems posed by the unavailability of data and the particular answers dilemma. The metamodel also provides a framework that combines viewpoints from different sectors and professions. By focusing on the services provided by critical infrastructures, ISE bridges the gap between the business and engineering views of critical infrastructures and accommodates the national security perspective. Furthermore, the sound mathematical foundation provided by the ISE metamodel supports analyses ranging from topological evaluations of dependency structures to statistical analyses of simulation results obtained using agent-based models.

Drawing from our experience with the telecommunications and electric power infrastructure modeling effort, we are currently creating detailed models of multiple critical infrastructures using the ISE metamodel. An integrated simulation environment called SimCIP based on the ideas presented in this paper is also under development.

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References

[1] M. Amin, Restructuring the electric enterprise: Simulating the evolution of the electric power industry with intelligent adaptive agents, in *Electric Pricing in Transition*, A. Faruqui and K. Eakin (Eds.), Kluwer, Norwell, Massachusetts, pp. 51–64, 2002.

[2] M. Baran, R. Sreenath and N. Mahajan, Extending EMTDC/PSCAD for simulating agent-based distributed applications, *IEEE Power Engineering Review*, vol. 22(12), pp. 52–54, 2002.

[3] D. Barton and K. Stamber, An Agent-Based Microsimulation of Critical Infrastructure Systems, Technical Report SAND2000-0808C, Sandia National Laboratories, Albuquerque, New Mexico, 2000.

[4] E. Casalicchio, R. Setola and S. Tucci, An overview of modeling and simulation techniques for critical infrastructures, *Proceedings of the Twelfth IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunications Systems*, pp. 630–633, 2004.

[5] Department of Homeland Security, National Infrastructure Protection Plan, Washington, DC (www.dhs.gov/xlibrary/assets/NIPP_Overview.pdf), 2006.

[6] M. Dunn, Understanding critical information infrastructures: An elusive quest, in *International CIIP Handbook 2006 – Volume II*, M. Dunn and V. Mauer (Eds.), Center for Security Studies, ETH Zürich, Zürich, Switzerland, pp. 27–53, 2006.

[7] Y. Haimes and P. Jiang, Leontief-based model of risk in complex interconnected infrastructures, *Journal of Infrastructure Systems*, vol. 7(1), pp. 1–12, 2001.

[8] K. Hopkinson, X. Wang, R. Giovanini, J. Thorp, K. Birman and D. Coury, EPOCHS: A platform for agent-based electric power and communication simulation built from commercial off-the-shelf components, *IEEE Transactions on Power Systems*, vol. 21(2), pp. 548–558, 2006.

[9] S. Panzieri, R. Setola and G. Ulivi, An agent-based simulator for critical interdependent infrastructures, *Proceedings of the Second International Conference on Critical Infrastructures*, 2004.

[10] D. Reed, S. Chang and T. McDaniels, Modeling of infrastructure interdependencies, *Proceedings of the Third International Conference on Critical Infrastructures*, 2006.

[11] S. Rinaldi, J. Peerenboom and T. Kelly, Identifying, understanding and analyzing critical infrastructure interdependencies, *IEEE Control Systems*, vol. 21(6), pp. 11–25, 2001.

[12] J. Saunders, A dynamic risk model for information technology security in a critical infrastructure environment, in *Risk-Based Decision Making in Water Resources X*, Y. Haimes, D. Mosher and E. Stakhiv (Eds.), American Society of Civil Engineers, Reston, Virginia, pp. 23–39, 2003.

[13] D. Schoenwald, D. Barton and M. Ehlen, An agent-based simulation laboratory for economics and infrastructure interdependency, *Proceedings of the American Control Conference*, vol. 2, pp. 1295–1300, 2004.

[14] W. Tolone, D. Wilson, A. Raja, W. Xiang, H. Hao, S. Phelps and E. Johnson, Critical infrastructure integration modeling and simulation, in *Intelligence and Security Informatics (LNCS 3073)*, H. Chen, R. Moore, D. Zeng and J. Leavitt (Eds.), Springer, Berlin-Heidelberg, Germany, pp. 214–225, 2004.

[15] W. Tolone, D. Wilson, A. Raja, W. Xiang and E. Johnson, Applying Cougaar to integrated critical infrastructure modeling and simulation, *Proceedings of the First Open Cougaar Conference*, 2004.

[16] S. Wolthusen, GIS-based command and control infrastructure for critical infrastructure protection, *Proceedings of the First IEEE International Workshop on Critical Infrastructure Protection*, pp. 40–47, 2005.