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A Modular Dynamic Simulation Model of Infrastructure Interdependencies

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Abstract

Infrastructure interconnections create chains of interdependencies that can propagate disturbances across many infrastructures and over long distances. The pattern of interconnections may tend to propagate, amplify, or dampen disturbances. System dynamics modeling can be to identify chains of interdependencies, arising from pervasive interconnection, which might create unexpected vulnerabilities or robustness. The scope of an infrastructure interdependencies model is necessarily broad; it must include a comprehensive set of interacting components to insure that critical pathways, which might involve distant locations and disparate infrastructures, are represented.

System dynamics models can play a crucial screening role in a comprehensive framework for making policy decisions affecting infrastructures. These models allow us to relatively quickly build coarse-grained system simulations that include many interacting infrastructures, and to identify the properties or interactions that might create failure cascades. We can quickly assess the uncertainty in the key results, identifying those areas in which more data or more detailed modeling would provide more conclusive results and less risk in decision making. The results of the screening analysis may, by themselves, provide sufficient resolution to reach decisions. If not, the screening process provides the justification and direction for additional data collection or modeling.

An infrastructure interdependency model for California has been constructed from a set of modular components, each of which represents a particular infrastructure, environmental condition, or economic sector. Each component model represents the relevant internal dynamics, such as input material management, that govern the behavior of the infrastructure element. These component models exchange signals, representing the flow of materials, money, and information. Configuring the component dynamic simulation models, and defining the way they are interconnected, creates a model of a particular system, such as the California electrical supply system and its associated customers, suppliers, and dependents.

This modular approach has several advantages:

- Models of individual components can be modified or refined independently of the models of other components. The effects of alternative models for a component can be easily explored. These model alternatives might reflect uncertainty about the component's properties. They might reflect alternate conceptual hypotheses about how the component may operate. Or they might represent specific changes in operating rules based on policy changes.

- The components developed for a particular analysis can be used in other analyses by defining the appropriate parameter values and interconnections with other model components.

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- The individual component models can be run and tested in isolation from other component models, which simplifies development and verification.

The general model features are part of a conceptual specification for infrastructure interdependency modeling; they do not depend on the particular system being modeled, or the particular goals of the analysis. Instead, they help to structure models of particular systems by organizing information about infrastructures and their interconnections.

Objects in the model fall into one of five basic classes: materials, networks, services, markets, and entities. Services and markets are special types of entities, but the model can include other kinds of entities as well. In general, entities exchange materials over networks. The elements of the conceptual model, and their distinctive roles and properties, are:

> *Materials*
> A material is anything that is exchanged among entities. Examples include natural gas, electricity, water, money, or information. All materials are exchanged over networks. A given material might move over only one type of network (e.g., electricity on the electrical transmission and distribution system), or a material might be able to move over many networks (e.g., information can move over land lines, satellite links, or through the postal system). Each material has at least one characteristic (an amount or level), but can have any number of additional characteristics that are carried along with it (such as a contaminant concentration in water).
>
> *Networks*
> A Network conducts material flows among entities. There are no *a priori* requirements regarding the structure of the network model. It might mimic the fine physical details of a distribution system, or a much coarser representation might be appropriate. A network performs two basic functions. First, it must associate a node with each entity that uses the network, and it must be able to report the status of that node through the network. Second, it must define a set of channels that are used to move materials between entity pairs.
>
> *Services*
> Services take in materials and add value by transforming them into output materials. For example, a coal-fired power plant will take in coal, water, and labor and transform it into electricity. Each input or output material flow is usually a commercial transaction, modeled by a customer/supplier relationship (see below). The way in which the output material depends on the input materials is entirely defined in the dynamic simulation model of the service. A given service might, for example, require a continuous supply of inputs in specific proportions, or may maintain inventories of certain inputs against supply interruptions.
>
> *Markets*
> Markets represent the way a set of material suppliers interacts with a set of customers for the material. Markets have one or more material suppliers, each offering their own price. They have one or more customers for the material, each paying a common price. Markets allocate aggregate customer demands among suppliers according to some set of rules. The rules are used to allocate demand, to determine the common price, and to control the flow of the material. The rules may vary from one market to the next as we attempt to capture the specific dynamics that are particular to each market. Material flows into and out of markets are usually associated with a particular network, although this is not mandatory.
>
> *Entities*
> Entities are any other objects in the model that exchange materials. They are more general than services or markets because they are not required to provide any specific interface to other model components. Examples of entities include the environment, regulatory agencies, or financial institutions.

The flow of materials between two entities establishes a relationship between those entities. Flows representing economic transactions follow a distinct pattern (the customer/supplier relationship) that occurs in many models. The customer/supplier relationship exists between a service (the supplier) and any entity that uses one of the materials produced by the service. The relationship consists of four separate material flows:

- The supplier provides price information over a communications channel;
- The customer sends a demand for the material over a (separate) communications channel;
- The supplier sends the material to the customer, generally over a channel in a network that is suited to transmitting the material;
- The customer transmits payment to the supplier over the financial network.

For some materials, the amount demanded is communicated implicitly through the distribution system, rather than explicitly through the communication system. Customers of municipal utilities, for example, immediately tap distribution systems rather than requesting specific quantities of water and electricity. For these materials, demand is communicated through state changes in the material distribution network rather than through a separate exchange over the communications network.

Entities may exchange materials other than through customer/supplier relationships. Regulatory agencies may communicate price caps to generators for example, or the environment may “communicate” conditions that influence or constrain an entity’s operation. These exchanges may occur over a network (as in the case of price caps), or may occur directly (as in the case of environmental conditions). There are no *a priori* constraints on these relationships.

The economic behavior of the entities in the model is reflected in the prices they set for the output materials they produce, and in the amount of input materials they demand at the offered price. Infrastructure disruptions can slow or interrupt material flows, leading to changes in demand for other input materials, or changes in the production rate of output materials. Longer-term changes in production functions, reflecting decisions about capacity expansion, might result from recurring interruptions.

The economic behavior of the entities in the model is entirely determined by the implementing component models. This flexibility allows the effects of alternative behaviors or rules to be readily identified by modifying the relevant component models.

The relationship between a service’s input material prices and output material prices and production can be defined in any way within the component model. A simple fixed production function, representing equilibrium material flows, might be appropriate in some analyses. In other cases, input inventory management dynamics might be modeled explicitly. The appropriate level of internal details and dynamics of the component model for a service depends on the specific analysis goals and uncertainties.

The behavior of markets, like services, is entirely determined by the implementing component models. They may assume instantaneous equilibrium between aggregated supply and demand, or they may contain buffering to accommodate supply/demand imbalances. Demand may be allocated competitively among suppliers, leading to a uniform supply price, or various auction-type allocations may be implemented. Supply shortages may be distributed among consumers; they may be allocated based on assigned customer priorities; or, they may use some other scheme. This flexibility allows the influence of alternative market structures on the overall analysis to be readily identified by modifying or replacing the component model.

Electric power supply in California depends on the successful interaction of a large number of processes, such as generator operation, power transmission and distribution, power marketing, and delivery of fuel to power generators. In the winter of 2000-2001, trends in power supply and demand, along with plausible load projections for a warm summer, were considered likely to cause widespread shortages in electric power supply in California. We developed a set of interconnected dynamic simulation models, based on the framework described above, to evaluate the potential costs of power outages, and the effectiveness of increased natural gas storage in improving power supply conditions.

The pricing behavior of storage services contains feedback loops through the commodity market. This feedback is responsible for some of the more interesting dynamical behavior observed in the model. During high demand periods, natural gas imports are constrained by pipeline capacity. The market price for gas therefore increases until storage services release rates satisfy residual demand. The increase in market price causes the storage services to increase their estimates of what constitutes “high” and “low” prices. In subsequent periods of high demand, the market price must be raised even higher before gas is released from storage.

In the model, the feedbacks and delays that couple natural gas prices to the amount of gas demanded result in periodic spikes in natural gas prices. Spikes of this magnitude were not observed in the historical record, indicating that the model has not adequately captured some elements of the market dynamics. Past experience with gas price increases, during periods of short supply, would presumably condition the estimated marginal costs of gas-fired generators, leading to anticipatory increases in the bid price for electricity. Such increases would deter the shift to gas-fired generation, somewhat forestalling the anticipated gas supply shortfall. Other factors not yet included in the model could tend to moderate natural gas prices: competition among gas storage facilities, an unwillingness to encourage new entrants into the market, price controls, and consideration of any joint ownership interests between storage facility operators and their customers. A more sophisticated model of price setting behavior would be needed to represent these effects.

Although observed natural gas prices do not show periodic spikes, the physical constraints that lead to price spikes in the model are a real feature of the infrastructures in California. These features have the potential to confer market power on the operators of gas storage facilities. As overall demand for gas increases, gas import and production capacities, rather than storage volumes, become limiting factors.

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