A Dynamic Simulation Model of the Effects of Interdependent Infrastructures on Emergency Service Response

Stephen Conrad, Theresa Brown, Walt Beyeler
Critical Infrastructure Surety, Department 6515
Sandia National Laboratories[1]
1515 Eubank, SE, MS 0451
Albuquerque, NM 87123
Tel. 505-844-5212/ Fax 505-844-8641
shconra@sandia.gov, tjbrown@sandia.gov, webeyel@sandia.gov,

Abstract

Models of telecommunications and emergency services were added to an existing infrastructure interdependencies model. The interdependency model tracks the flow of materials between infrastructures and other services. Telecommunications was represented in the model using bandwidth as a commodity that is supplied and consumed. The resulting model was used to evaluate alternative service restoration sequences for catastrophic disruptions caused by the an earthquake, and to evaluate whether or not service restoration priorities and sequences will significantly alter the potential death toll, the extent of physical damage, or utility service restoration times. The results of the analysis can also be used to identify data needs and model enhancements for improving model utility and portability.

The model can be used to investigate a wide range of ideas for potentially improving emergency response and disaster recovery. We want to find the leverage points in a particular system that will allow for overall improvement of emergency responses. We utilized a California earthquake as a test case because it entails widespread and severe disruption to many infrastructures. Since the mid-1980's, LA has worked hard to improve disaster (earthquake) recovery. All the obvious improvements have already been made. The ones that are left to make are less obvious and likely can be identified through a better understanding of the interplay between interacting infrastructures. Building and exercising the model helps us develop this understanding.

Modeling Consequences

A general model structure was used to represent damage to distribution networks (roads, power transmission and distribution lines, pipelines) and to buildings in the commercial, industrial, and residential sectors. This structure was replicated in the individual dynamic simulation models of the networks and sectors. In each case, there is an initial amount of intact physical capacity stock. This stock can be in one of four states: (1) intact, (2) uncontained damage-- which means it is damaged in a way that can propagate (e.g., on fire), (3) contained damage – which means it is damaged in a way that cannot propagate

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(e.g. a collapsed building), or (4) controlled. The quake moves intact stock to both the uncontained and contained states. Stock in the uncontained state can damage both intact and contained stock. Contained stock can also move spontaneously to the uncontained state (e.g., natural gas leaks get sparked). Both uncontained and contained stock can move to the controlled state, which represents structures that are unusable but no longer in need of immediate attention. Stock can become controlled at a "natural" rate (e.g., fires that burn out by themselves) augmented by an "active" rate, which requires resources (e.g. fire trucks). If these resources aren't provided (at an adequate rate), then damage can spread. The model includes the effect of repairs, which move stock from the controlled state to the intact state at the cost of some input materials.

The model tracks injuries to people that result from direct and indirect damage to structures. People can be in one of four conditions (stable, injured, seriously injured, or dead) and in one of four contexts defined by the physical structures: intact, uncontained, contained, or controlled. People move from context to context as the structures they are in move from one class to another, but they can also be evacuated to the controlled context spontaneously or through the application of emergency services. People in the seriously injured condition die at a rate determined by their context, and require emergency services to move to a stable or simply injured condition. Injured and seriously injured people can also be moved to remote service locations (e.g. hospitals) if the right services are provided.

Modeling Response and Effectiveness

Modules representing fire, medical and police emergency services were developed and added to the infrastructure interdependency model. Modifications to the infrastructure modules were made to account for specialized repair labor availability. Potential delays due to transportation and communication system disruptions and capacity limitations were also included. Since repair times are a function of the equipment damaged and the inventories of spare parts as well as the scale of the damage, and this level of detail is not yet included in the model, nominal repair times are input to the model and scaled according to the transportation and telecommunication systems status. Evaluating the potential effects of the uncertainty in repair time for individual infrastructures will provide an indication of the value of adding more detail to the model.
Emergency services are used to contain and control damages to people, property and restore infrastructure services. We assume that emergency responders have the following goals in order of priority regardless of the nature or cause of the emergency:

- Preserve and protect human life
- Prevent additional damage
- Restore infrastructure services
- Repair and rebuild damaged buildings

Although the goals are clear, they do not necessarily lead to a clear-cut sequence of responses because circumstances may cause conflicts. For example, restoring electric power to a hospital might lead to fire in an area with natural gas leaks. Sometimes restoring infrastructure services may emerge as a very high priority because the effectiveness of the emergency response is contingent on that infrastructure. For example, loss of telecommunications may adversely impact dispatching or the need to transport diesel to fuel back-up generators for life-saving equipment might make establishing a transportation pathway a high priority.

In this analysis restoration options are compared based on their ability to meet the first three goals -- preserving life, limiting the damage, and restoring services as quickly as possible.. An option that accomplishes all three goals faster or more completely is considered a better option than one that only accomplishes a fraction of the goals or requires a very long time to complete them.

Modeling Telecommunications

The goal of our systems level model of infrastructure interdependencies is to identify potential controlling factors and dynamics using a relatively simple model rather to simulate the detailed behavior of all the interacting components. The model of telecommunications developed for this analysis simulates its role in controlling other infrastructures and coordinating services, with the service-level state of the telecommunications system as a primary metric.

Any user of telecommunications can subscribe to one or more services (e.g., wireline, cellular, pager, internet). The service allows them to send or receive information (or both) with possible limitations on the format or rate. A particular service might also provide customization, such as high-security transmission. For an individual user, each service is either on or off at any time. Each subscription represents a commitment by the service provider to supply a certain amount of bandwidth. Bandwidth may be oversubscribed based on observed utilization. Simultaneous demand for reserved bandwidth by many customers may exceed the available bandwidth, producing service interruptions.

This simple, systems-level modeling can be used to simulate the potential effects of providing priority telecommunications service to emergency response and infrastructure repair crews and to analyze the potential for mitigating telecommunication disruptions during mass calling events. Currently, telecommunication network management controls are instituted to throttle back traffic demand entering a disaster area by allowing only outbound calls. Other management controls are instituted such as providing priority phone services like GETS (Government Emergency Telephone Service) and rerouting traffic to exploit spare capacity in outlying areas. For cellular, mobile cell towers can be deployed and calls redirected to increase capacity to handle cellular calls in the local area. All these actions effectively expand the bandwidth to emergency response workers while also having repercussions for all other users. There may be other strategies for effectively expanding bandwidth during emergencies that could be incorporated into the model to evaluate their potential effectiveness, such as using cell phones like a pager to send short messages (“I’m OK” or “need help”).

Bandwidth is modeled as a commodity that is similar to electric power. There is large variation in demand over short periods, it cannot be inventoried, it must be provided in real time, and some users may be able to provide local back up. The demands of individual users are not usually significant, and are not an explicit consideration in their short-term decision-making, however satisfying aggregate demand using the current supply capacity is an important operational concern for providers.

Modeling bandwidth as a commodity provides a structure for identifying the imbalances between demand and physically constrained supply, which may lead to service interruptions, and relating these interruptions to conditions in other infrastructures.

Model Application

The model was used to evaluate the potential benefit of prioritizing telecommunications service to the emergency responders. It was also used to evaluate a strategy of placing highest priority on restoring infrastructure services to emergency service providers. The model was also used to evaluate how the time of day, hence the differences in people's location and behaviors, influence the effectiveness of emergency services and the sensitivity of the model results to infrastructure service prioritization.

For the input used in this analysis, we found that prioritizing telecommunications made a small but significant difference in the ultimate number of fatalities. We also found that the effectiveness of emergency services was not significantly hindered by infrastructure damage. Although the delivery systems for power, natural gas, and water, along with the transportation system, suffered large capacity losses, the emergency services were not constrained by interruptions in the availability of key materials. They were able to provide services faster than the rates at which structural damage could spread or human injury worsen. As a result, restoring infrastructures to emergency services provided little response benefit, and slightly increased restoration times to other infrastructure users. However, we believe that improvements in modeling the transportation infrastructure could disclose other constraints on delivery of emergency services and suggest policies that could help relieve those constraints.

The results indicate that the model can be used to evaluate emergency response priorities and potentially improve emergency response through a better understanding of the interdependencies. This type of analysis can be used to identify areas where more detailed modeling and data analysis would be of benefit.

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