♦ Inter-Infrastructure Modeling—Ports and Telecommunications

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During the past year, Bell Laboratories and Sandia National Laboratories have been modeling and simulating cross-industry interactions between infrastructures and the cascading of impacts under disruption scenarios. Critical national infrastructures for importing and exporting goods and materials (e.g., seaboard shipping through ports on the U.S. East and West Coasts) require the support of other industries to conduct business. For example, ports rely on the grid of information networks (voice, data, Internet) to communicate; they also rely on the power grid to operate machinery and the transportation grid to distribute the goods and materials. While information networks, power networks, and transportation networks tend to be highly reliable, disruptions can lead to extended outages requiring days/weeks to repair. These outages can cause shutdown of port operations, resulting in severe financial losses for the economy. This paper describes just one of those inter-infrastructure dependencies: by simulating a port and the interactions with the telecommunications infrastructure, it describes the impacts on both the flow of goods and materials through ports and the economic impact on the ports under a telecommunications disruption scenario. © 2004 Lucent Technologies Inc.

Background

Disruptions to our critical national infrastructures (e.g., power, telecommmunications, shipping) are areas of increasing national concern. For example, since the events of September 11, 2001, container shipments through U.S. ports are believed to be a potential pathway for the introduction of weapons of mass destruction into the United States, thereby threatening homeland security. New security measures have been implemented, and others have been proposed, in an effort to reduce this perceived threat. These measures call for additional processes and equipment in container shipment to better characterize and control cargo. Much of this requires increased reliable communications. Requiring new security measures can change important performance characteristics of the port such as the time and cost required to import and export goods. These performance changes can suppress overall demand for shipping and change the relative attractiveness of ports to importers, exporters, and cargo carriers.

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Successful port operations require the coordinated action through communications of many disparate people and organizations, including ship owners, port authorities, importers and exporters, labor unions, and government agencies. Port operations depend on reliable performance of various infrastructures, including electric power systems, telecommunications systems, and petroleum refining and distribution systems. Understanding the potential for disruptions caused by infrastructure interactions is one goal of the effort to make infrastructures more secure [6]. We are therefore interested in the sensitivity of port performance to infrastructure disruptions; specifically, we focus on this question: What are the conditions that cause infrastructure disruptions and how will those disruptions impact port operations?

There are two primary time scales of interest in this problem [1]. First, the mechanics of port operations and its performance in response to disruptions operates on a time scale extending over days and weeks to months. Second, long-term competitiveness and economic viability of a port—especially in shouldering the burden of paying for increased security measures—play out over a time scale that extends over years to more than a decade. Here we hypothesize that, similar to many system dynamics problems [2, 5], cause and effect may not be closely related in time. In this paper, we focus on the short-term impacts of telecommunications disruptions.

Panel 1. Abbreviations, Acronyms, and Terms

DTRA—Defense Threat Reduction Agency
NISAC—National Infrastructure Simulation and Analysis Center
N-SMART—Network Simulation Modeling and Analysis Research Tool
PSTN—public switched telephone network

Introduction and Overview

To help define and explore the tradeoffs between security and commerce, we have used system dynamics models to engage diverse representatives of business and government. In collaboration with domain experts, we have developed models of port performance to simulate the effects of a variety of security measures on port operations under both normal conditions and conditions characterized by several disruptions in supporting infrastructures. The system dynamics model represents the flow of containerized goods through a port under normal conditions, under scenarios that include the effects of various measures to enhance security, and under scenarios when the port infrastructures are disrupted.

The status of the infrastructures used in port operations (electric power, telecommunications, and motor fuel) influences the way in which critical port operations can be performed. Infrastructure status is not simulated in the port operations model, but it is specified as part of the definition of a disruption scenario. The status of the telecommunications infrastructure was derived from detailed simulations of network performance subject to the disruption considered in the scenario. From this simulation, the status of the telecommunications infrastructure servicing the port was summarized as an efficiency function. This function was used in the port operations simulation to examine the effect on container flow. The telecommunications infrastructure was one of the critical infrastructures given special attention in this analysis because it is critical for both normal port operations and recovery operations after a disaster. Telecommunications is not only critical for operations within the port, but for communications links from the port to other critical infrastructures supplying services required by the port. **Figure 1** shows the telecommunications industry's central role in inter-infrastructure communications [6].

In the section immediately below, we describe the structure of the port operations model and general disruption scenarios. In the section following it, we discuss the modeling of these disruptions as simulated by a detailed telecommunications network model and the effect of telecommunications disruptions on various aspects of the port operations model. We then present representative results showing how cargo throughput volume is degraded by the disruption.

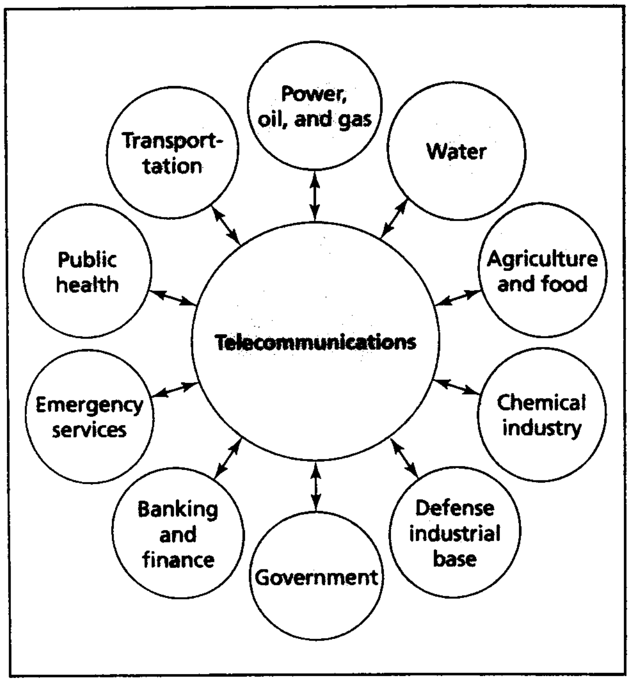

Figure 1.
Dependency of critical national infrastructures on telecommunications.

Approach to Modeling Port Operations

The port operations model is designed to provide an understanding of the robustness of port operations to disruptions under different conditions and to evaluate the ability of the port to recover from such disruptions.

Figure 2 shows a simplified stock and flow structure for moving import cargo containers through a port. There is also a corresponding outflow of export materials (not shown).

Telecommunications play an important role in this operations model in a number of ways. Telecommunications are required:

- To process import/export paperwork and ship manifests;
- To order labor for loading and unloading ships and for terminal operations;
- To order trucks to pick up import cargo on the terminal; and
- To arrange for export cargo to be delivered and accepted at the port.

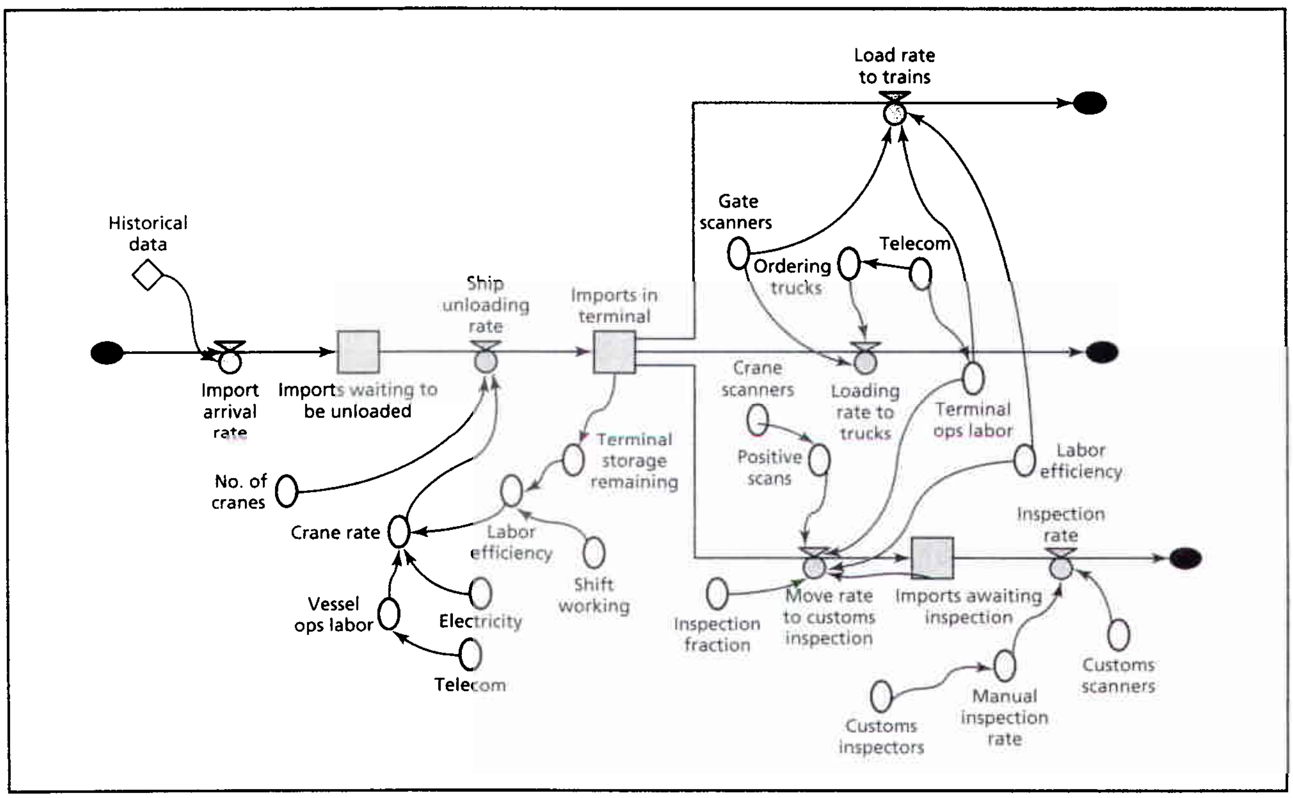

Figure 2.
Port operations dynamic model.

We model five container terminals operating at the port. The flow of containers at each terminal is divided into two segments:

- *Vessel operations.* These operations comprise the loading and unloading of ships. Rates of loading and unloading depend on work schedules, the number of labor gangs and cranes available, terminal efficiency given shift conditions (e.g., work is somewhat slower at night) and the density of containers on the terminal, and the availability of electric power for cranes. Import containers are divided into three categories: those destined for trucks, those destined for trains, and those destined for customs inspection as they are unloaded.
- *Terminal operations.* These operations include the moving of containers on the terminal, the loading and unloading of trains and trucks, and gate operations for processing paperwork and managing the arrival and departure of trucks. The rate at which terminal operations proceed also depends on availability of labor and on terminal efficiency. In addition, terminal operations depend directly on telecommunications and diesel fuel.

Import containers that require inspection are moved to an off-terminal inspection station. The additional time required to inspect a container depends on the time required to move the container to the inspection site, the work schedule of the inspectors, the number of available inspectors and scanning machines, and the time required to inspect a single container. The time to inspect a container, in turn, depends on the thoroughness of the inspection and the type of scanning equipment.

The nominal rate at which import and export containers arrive at the port is based on historical data. The data period for the simulations presented here extends from the beginning of January through the end of May 1999. Simulated containers may arrive at slower rates than indicated by the historical data if the simulations include disruptions to telecommunications or fuel or if the port becomes sufficiently congested.

Container Security

Over the past two years, a variety of container security policy options have been proposed. These include increased manual inspections, port of departure inspections, and supply chain assurance; earlier manifest reporting, improvement of container seals; and installation of scanners of various types at port terminals. The port operations model has been constructed to allow the user to invoke all these security options, either singly or in combination. (See [3] for an extended discussion on port security.)

Potential Disruptions to Port Operations

Potential disruptions to port operations exist in a number of areas:

- *Telecommunications.* A major telecommunications disruption might be a fire that destroys all or part of a telephone central office building, thereby eliminating telephone service in the surrounding area, including the port.
- *Electric power.* An avalanche in nearby mountains might take out several major transmission lines, resulting in rolling blackouts that reduce the productivity of both day and night shifts at the port by a significant fraction over several days.
- *Labor.* A strike or lockout might occur that, in the first week, significantly affects throughput as "work to rules" is imposed. Then, for the following several weeks, a strike or lockout might occur.
- *Port security.* A dirty bomb might be discovered during a customs inspection at another nearby port, causing that port and also the simulated port to be closed for a period of time. Then, it is decided to increase the number of customs inspections after the event. The rationale for including the effects of disruptions in the port operations model was based on intuition from previous work on infrastructure interdependencies. We suspected that imposition of new security measures might exacerbate the effects of disruptions, so we included the ability to consider disruptions in the model in order to observe the interplay between disruptions and additional security measures. However, we learned as we implemented disruptions at the port that, in the face of major infrastructure disruptions, the port will simply shut down. For example, the container cranes run on electricity. When an electrical power disruption occurs, the cranes no longer operate. If this condition persists for any

appreciable length of time, port operations must cease until power is restored. Secondarily, we hypothesized that imposition of security measures might impede the recovery from disruptions. Again, our intuition proved amiss. By exercising the model, we learned that crane moves are the rate-limiting step in port operations. This makes sense, as the cranes are by far the largest capital expenditure on the terminal. Since none of the security measures impeded the rate of crane moves, they would not be expected to impede the recovery from disruptions.

In this paper, we focus only on the telecommunications disruption as an example.

Modeling Telecommunications Disruptions

There are many potential types of telecommunications disruptions—from fibers being cut by backhoes to switching and transmission equipment being destroyed by fire, vandalism, contamination, or corrosion. Our example in this paper deals with disruptions caused by a fire that destroys several floors of a major telecommunications central office building housing both switching equipment and transmission equipment serving the port area. Not all of the building is destroyed. The cable vault in the basement remains operational, which means that all of the access plant from surrounding businesses and residential customers into the building remains ready to operate when new equipment becomes available. Office space in the building, which is not affected by the fire, is converted to house the replacement switching and transmission equipment. This disruption causes wireline communications to be severely impacted for one week. In the first day or so, this negatively affects the ability to assemble pilots, linesmen, other labor, and tugs as well, but workarounds are implemented fairly quickly through wireless communications and other telecommunications rearrangements, such as rerouting PBX to central office trunks to surrounding central offices not affected by the disruption. However, these alternatives take time to implement, especially since changes in port processes are needed because of their reliance on fax communications; so this disruption persistently affects the logistical communications needed to deliver cargo by truck to the port and to truck import cargo off the terminal. Following the first week, we assume that wireline telecommunications gradually recover over the next three weeks with the replacement of all the damaged equipment with new equipment from telecommunications equipment manufacturers. In all, full telecommunications recovery takes a month.

The N-SMART Simulation Model

Bell Labs has developed a discrete event simulation model—the Network Simulation Model Analysis Research Tool (N-SMART) [4], which simulates a complete metropolitan area on a call-by-call basis. **Figure 3** shows the components of the model that takes a description of a metropolitan area in terms of residence and business demands and traffic loads and then simulates the network on a call-by-call basis, taking into account customer re-attempts when calls do not complete (are blocked).

We use this simulation model to evaluate the impact of disruptions. For example, we might destroy a main central office building in the port area and model the resulting call completion probabilities for the entire area. **Figure 4** shows the resulting probability of blocking throughout the area after the main building has been down for just one day. When the main building goes down—say, at 10:00 on day 1—call blocking throughout the area jumps to 90% and more. At 11:00 on day 2 (on the right of Figure 4), the blocking levels rapidly return to normal levels. Since this simulation involves millions of calls and re-attempts, the run time takes tens of minutes to run on a workstation. As such, it cannot be run in real time working simultaneously with the port operations model, which is an interactive real-time simulation model. Hence, we need to abstract the results of the detailed call-by-call simulations of multiple scenarios and input them in a simple manner into the port operations model.

The interworking of the two simulation models is depicted in **Figure 5**, where the telecommunications simulations are run (not in real time) to depict many types of disruptive events. The outputs are converted into a scheme for a particular event called the aggregate telecommunications efficiency index. It is a

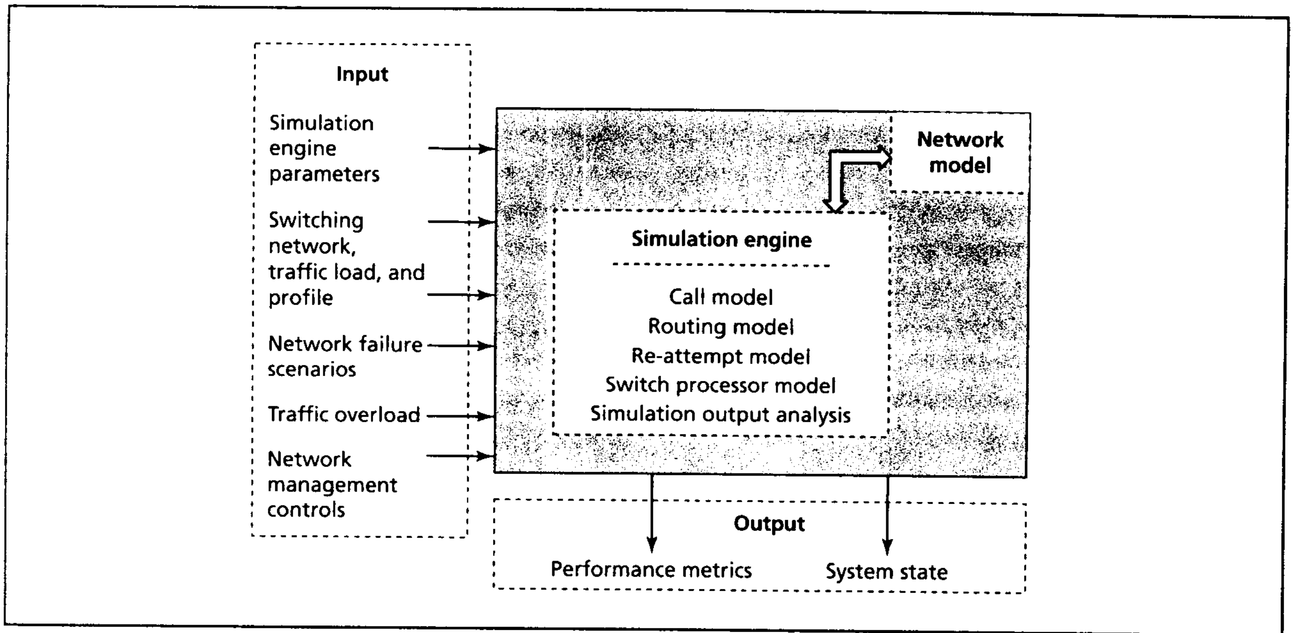

Figure 3.
N-SMART telecommunications simulation components.

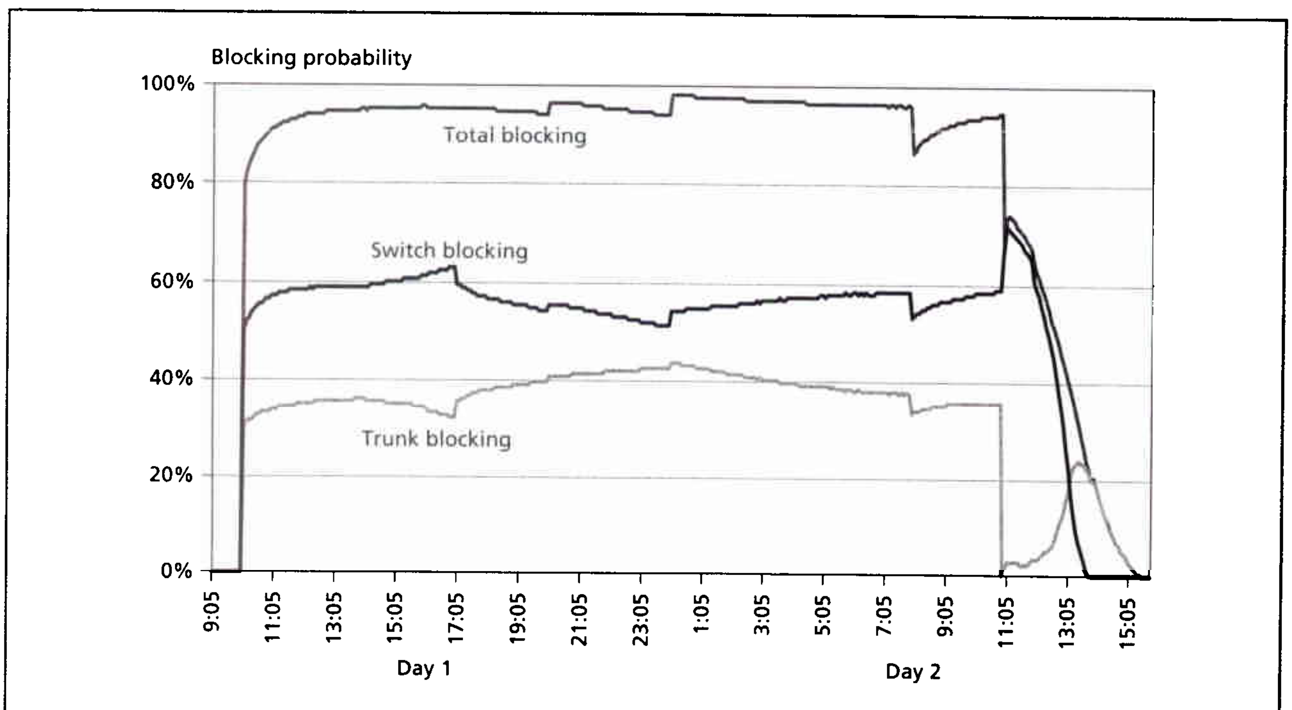

Figure 4.
Blocking levels with main building down for one day.

simple way of describing the likelihood of making a call through the network in distress. This then can be input directly into the system dynamics model for the port that runs interactively in real time.

An example of the aggregate telecommunications efficiency index is shown in **Figure 6**. Here we have plotted the probability of completing a call as a function of the number of tries by the person making the

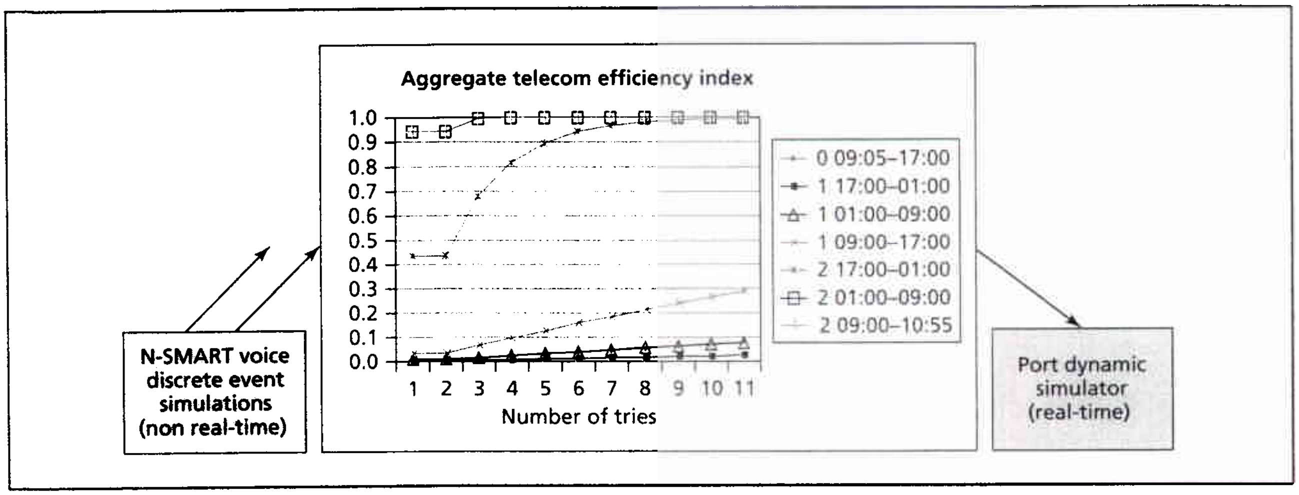

Figure 5.
Interworking of dynamic simulation and discrete event simulation models.

call for a number of different time periods. A time period in Figure 6 is identified by the day and work shift. Day 0 is the first day of the simulation. For example, the light blue line in the middle of the figure represents the telecommunications efficiency index for day 1 from 9:00 to 17:00.

Model results such as those shown in Figure 6 provide insight into the system recovery time following restoration of the damaged equipment posited in the disruption scenario. The time to obtain and install such equipment is also an important factor affecting service restoration, and thereby the telecommunications efficiency experienced by port workers. Large replacement switches would not typically be immediately available; we have assumed they could be obtained in one week. We have further assumed that three weeks would be required to install and test the replacements. For simplicity, we have assumed that the efficiency recovery curve is linear following service restoration. The resulting efficiency index used in the simulation of port operations is shown in **Figure 7**.

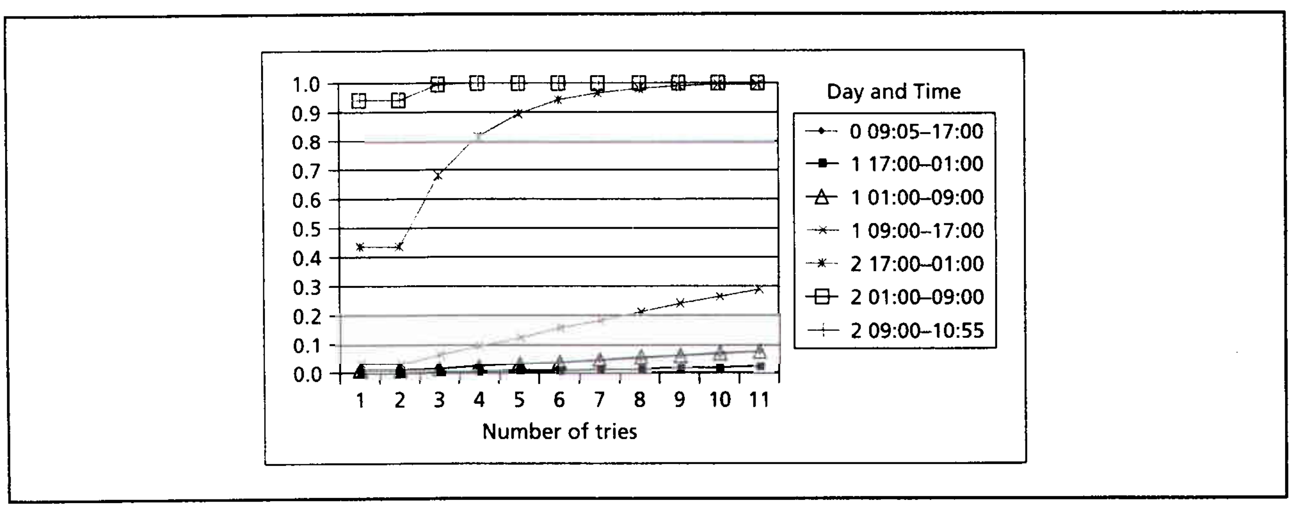

Figure 6.
Example of aggregate telecommunications efficiency index.

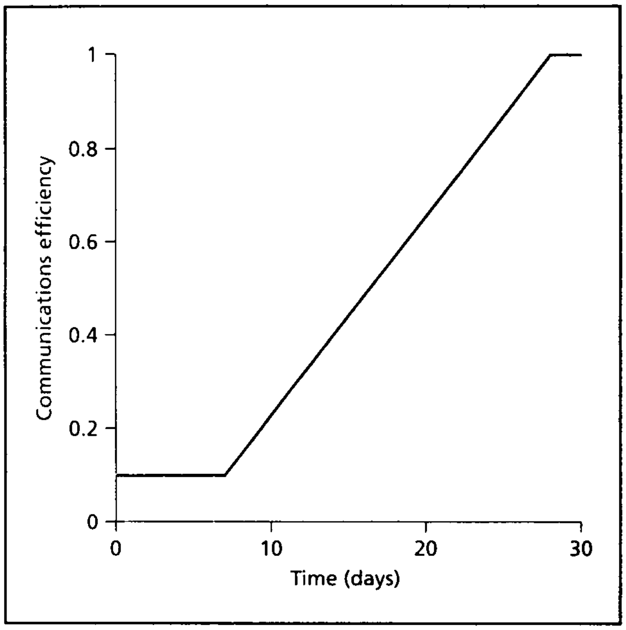

Figure 7.
Telecommunications efficiency used in the port operations model.

The Port Operations Model

The telecommunications efficiency function shown in Figure 7 was used to simulate the influence of communications service degradation and recovery on diverse aspects of port operations. **Figure 8** summarizes the flow of information required for maritime shipping. Bills of lading, manifests, and various notifications must be transmitted, and labor must be ordered. Communication delays impede the process. All these information transactions rely on telecommunications. Labor and trucking are ordered by telephone, while data is transmitted via either fax, private networks, or the Internet. In the port operations model, we assume that data transmissions via private networks and the Internet remain unaffected by the telecommunications disruption we have imposed and that workarounds such as using couriers for document delivery and using two-way radio on the terminals can limit the effects of the telecommunications disruption.

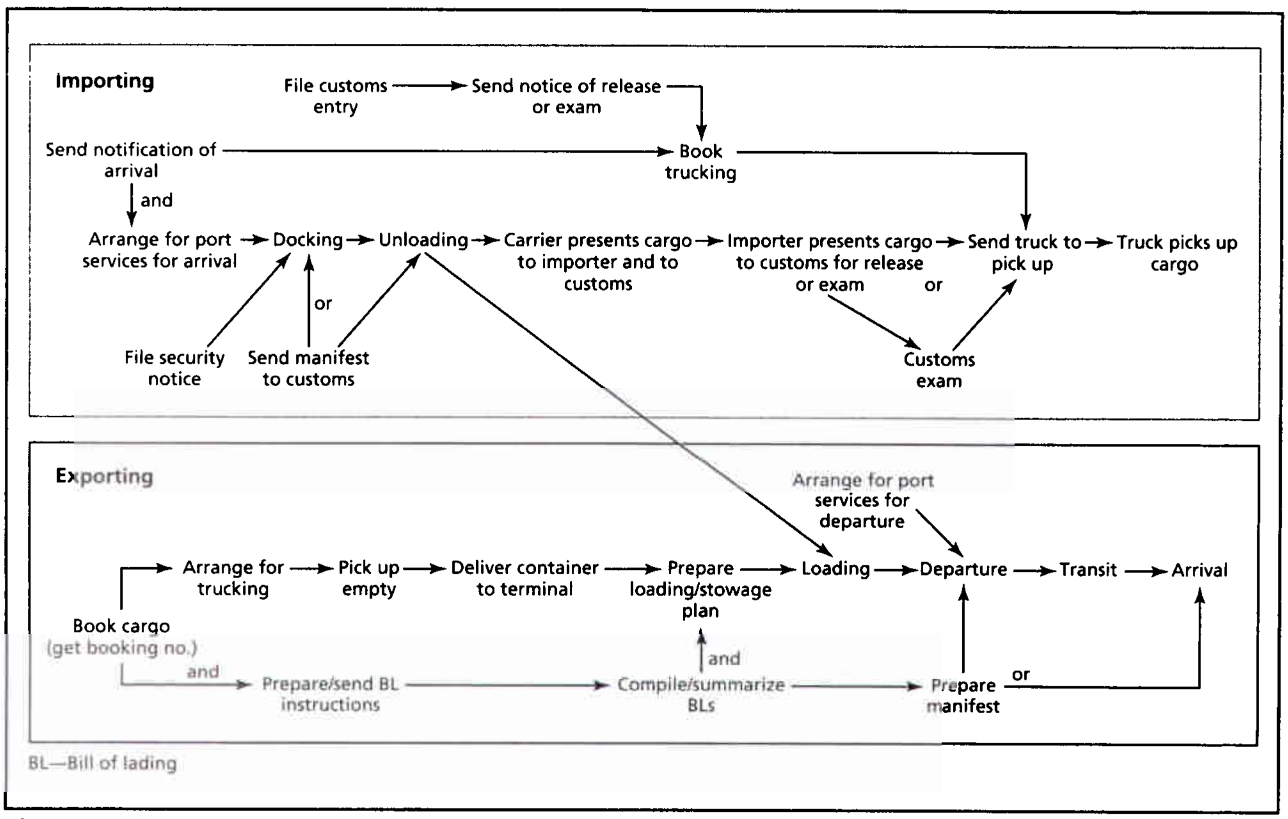

Figure 8.
Cargo and information flows from a port operations perspective.

In the model, a simulated port manager determines the desired amount of labor for each work shift by considering the amount of work to be done (containers to be loaded, unloaded, or moved) at the beginning of the shift and setting goals for the minimum time to complete the work. However, the pool of available labor is limited, as is the equipment (e.g., cranes) that labor requires. The manager therefore orders as much of the desired labor as is available, considering all constraints. The available labor will arrive to work if telecommunications are functioning normally. During telecommunications disruption, labor will arrive in proportion to an index (labor communications efficiency) describing the impact of telecommunications disruptions on labor ordering.

Labor communications efficiency differs from communications efficiency because we assume that it is relatively easy to find workarounds to communicate with employees about the shifts they are expected to work. Workers could, for example, travel to a central location to view posted assignments. We assume, therefore that labor communications efficiency at a given time is equal to the communications efficiency plus some additional amount of efficiency representing the workarounds. The algorithm for computing labor communications efficiency makes two key assumptions. First, there is a maximum value of labor communications efficiency that can be obtained adding efficiency due to workarounds. We assume a value of 0.8 in the simulations presented here. If communications efficiency is greater than 0.8, labor communications efficiency is assumed equal to communications efficiency. If communications efficiency is less than 0.8, labor communications efficiency, including workarounds, cannot exceed 0.8. The second assumption is that the gap between labor communications efficiency and the assumed maximum value of 0.8 is closed according to an exponential decay function. The rate of decay in these simulations is assumed to be 0.3 times the existing gap over each eight-hour shift.

Figure 9 shows, for example, the labor communications efficiency resulting from a square wave function for communications efficiency. The overall impact of telecommunications disruptions on labor ordering is relatively small using this algorithm because workarounds are assumed to be very effective. In this example, communications efficiency experiences a reduction to a value of 0.4 for 3 days and then recovers to normal.

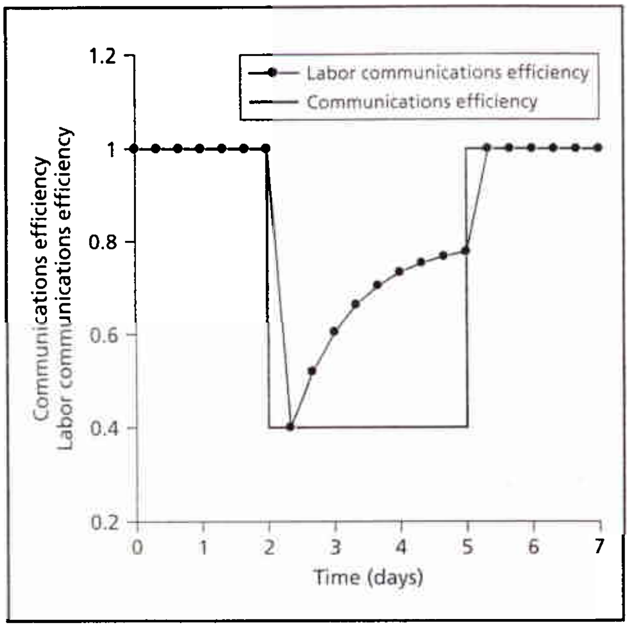

Figure 9.
Labor communications efficiency and communications efficiency versus time.

One important interdependency between telecommunications and port operations is the ordering of trucks to haul away import containers that have been unloaded from ships. Multiple communications are required, including possibly notification to customs officials that a container has arrived, notification from customs that the container is either released or needs to be inspected, notification to the receiver that the container can be picked up, and notification to a trucking company that the container can be hauled away. Any breakdown in this communication chain results in containers accumulating at the terminal.

We make two main assumptions about how the truck ordering process responds to a telecommunications disruption. First, we assume that if the disruption is not too severe, additional effort can be made to place calls. For example, if the reason for an incomplete call is network congestion, then repeated

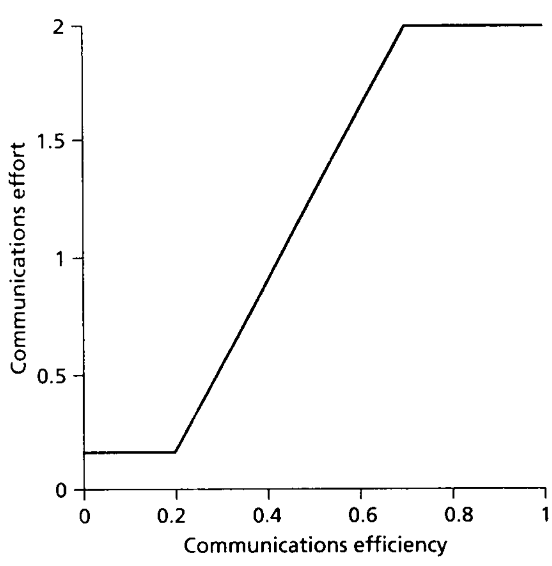

Figure 10.
Communications effort versus communications efficiency.

re-attempts may get the call through. In these simulations, we assume that the maximum level of effort is twice the normal effort. Second, we assume that, below a communications efficiency of 0.2, it is no longer cost effective to attempt truck ordering and effort is zero. In between these two extremes, we allow the effort to vary linearly with the communications efficiency. **Figure 10** shows the assumed value of communications effort as a function of communication efficiency. For example, if communications efficiency is equal to 0.4, the corresponding value of communications effort in Figure 10 is 0.8, meaning that, even though telecommunications are significantly impaired, there will still be some effort to place truck orders. The telecommunications effort of 0.8 reflects the competing needs to reduce the accumulating volume of containers requiring truck transport against the inefficient use of labor in placing orders while the public switched telephone network (PSTN) remains significantly impaired.

The simulated terminal labor at the port orders a truck at a time after an import container that is to be transported by a truck is unloaded or after a container that has been inspected is returned to the terminal floor. Orders are placed only during shifts that are staffed by terminal and gate workers. The product of communications effort, communications efficiency, and the normal truck ordering rate determines the rate at which these orders that are successfully placed. Continuing the example from the preceding paragraph, communications efficiency is equal to 0.4 and communications effort is 0.8. Consequently, the truck-ordering rate will be only 0.32 times the normal rate. This value is obtained by multiplying the communications efficiency by the communications effort. Trucks successfully ordered arrive to pick up containers after a specified delay.

Unsuccessful orders are placed into a backlog. An attempt to clear this backlog over the next work shift adds to the demand for telecommunications. Backorders are accumulated when demand for trucks exceeds the ordering capacity, and they are filled when capacity exceeds demand.

We note that not all import containers are transported by truck. Trains can also transport import containers in these simulations. We assume that telecommunications disruptions do not impact train arrival because trains tend to operate on fixed schedules. We assume that containers waiting for trucks cannot be transferred to trains because the destinations of trains and trucks do not tend to overlap.

An analogous chain of communications must occur in order for an export container to be received at the port. A portion of these communications involves clerks at the port. The impact on arrival of export containers due to telecommunications disruptions is similar to the impact on truck ordering. Arrival of exports can be backlogged if attempted communications are not successful. This backlog of export arrivals typically results in a greater than normal arrival of export containers after the disruption is over.

There are, of course, also communications required in order for ports to receive imports. We assume that telecommunications disruptions do not slow arrival of imports because the disruption scenarios considered in these simulations are not likely to impact international shipping communications.

Results of Telecommunications Disruption on Port Operations

Figure 11 summarizes the impacts to port operations from the telecommunications disruption. The base case (normal operations) is shown in black and disrupted operations are shown in either blue or gray. The disruption occurred on 2/1/1999.

- We see in Figure 11(a) that, almost immediately after the disruption, the volume of cargo on the terminal began to increase because trucks to pick up cargo could not be ordered due to impaired telephone communications. The container volume building up on the terminal would have been greater but for the concurrent decrease in

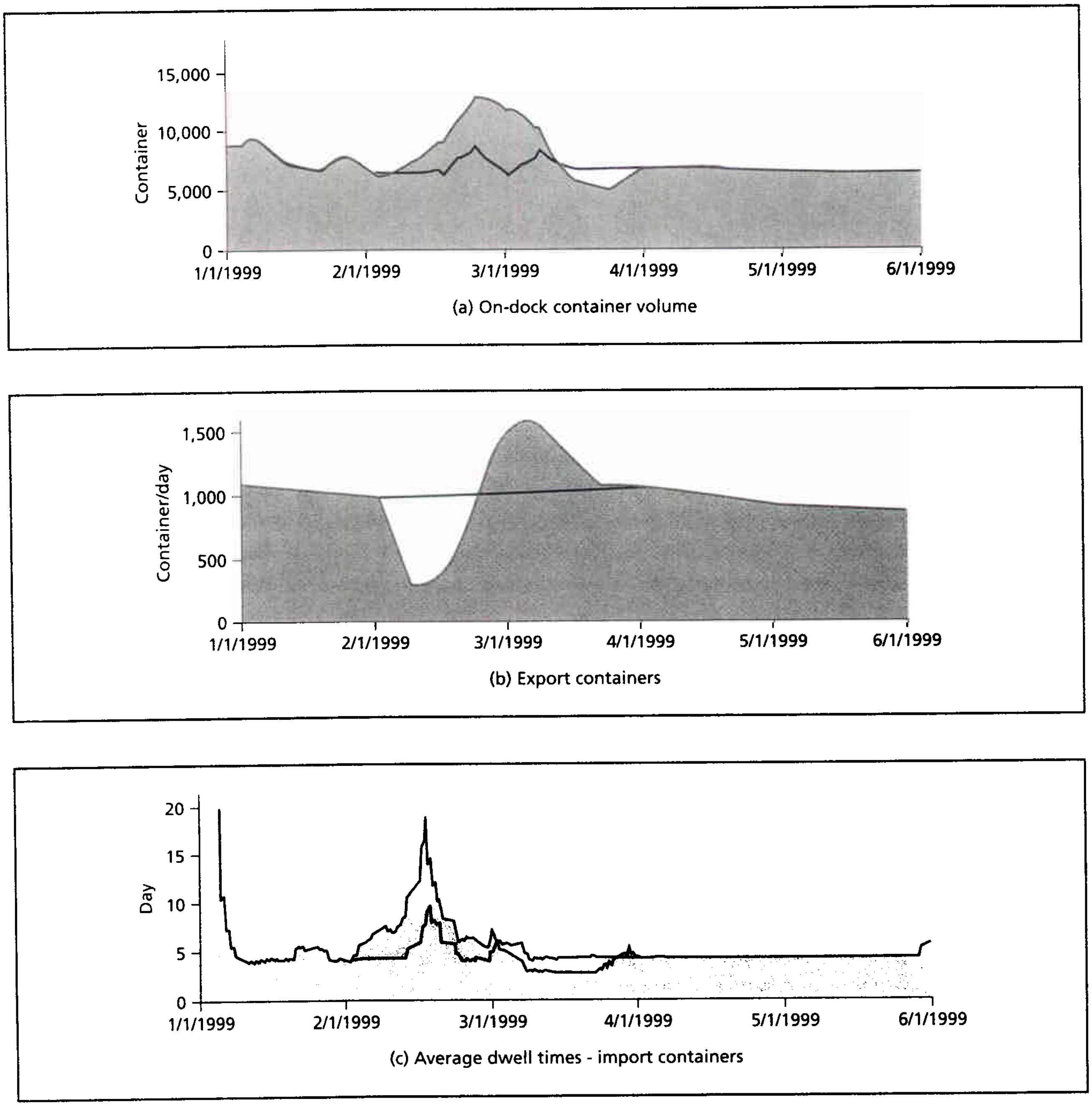

Figure 11.
Telecommunications disruption results.

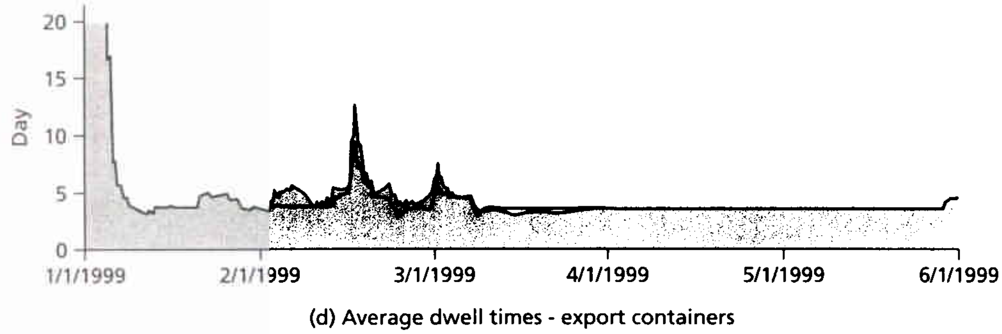

Figure 11.
Telecommunications disruption results (continued).

export containers arriving at the terminal, as shown in Figure 11(b). The arrival of export containers decreased because booking numbers could not be obtained and empty containers—to be filled and returned to the terminal for export—could not be picked up. In this disruption scenario, once telecommunications began to recover somewhat (≈40% efficiency, on about 2/15/1999), the port added a night shift for terminal labor to help clear the backlog of cargo. This labor provided information and documentation needed to order trucks, loaded and unloaded trucks, and staffed the terminal gates. This allowed more import containers to be picked up, but container volume on the terminal continued to increase because backlogged export containers then began to show up at the terminals. Container volume on the terminal peaked just before the beginning of March, just as all telecommunications repairs were being completed and telecommunications efficiency returned to normal. By the end of the first week in March, the surge in export containers had peaked. After this peak passed, terminal container volume rapidly returned to normal by the end of the second week in March. From mid-March through early April, the container volume on the terminal remained below normal as the second labor shift cleared out imports while working off the remaining backlog of exports. By the beginning of April, the volume of export containers arriving at the terminals had returned to normal and the night shift of terminal labor was no longer required. It took about two full months for port operations to return to normal.

- Container dwell times are shown in (c) and (d) of Figure 11. The dwell times for import containers are believed to be fairly accurate. However, the dwell times for export containers are significantly underestimated. Because of difficulties in arranging for trucking, exports remained on farms and **in** factories and did not queue up at the port to be included in the dwell time calculations. (Therefore the **costs** to customers associated with increased dwell times for exports are underestimated as well.) Peak dwell times for imports occurred in the third week in February and reached almost 20 days-about four times normal. (High dwell times shown for early January are associated with model startup and should be disregarded.)

Table I shows the summary costs of the disruption per import container over the course of the disruption and recovery period of about two months. Ship operation costs about $60,000 per day. Just after the disruption occurred, a lack of vessel labor slowed the loading and unloading of container ships. Later, the bulge in backlogged export containers showed up and required additional time to load. These delays added about $12 per container to be borne by the marine carrier. Increased container dwell time reflects the lost opportunity cost to customers

Table I. Summary of costs per telecommunications disruption.

Reason	Costs per container
Increased ship idle time	$12
Increased container dwell time	$ 5
Additional labor	$11
Total	$28

whose cargo has been delayed. At the peak dwell time, these costs reached levels of about $200 per container (based on an average cargo value per container of $80,000). These costs were minimized by putting on a second shift of terminal labor to help speed recovery from the disruption. These costs do not include supply chain difficulties at manufacturing locations due to delays in shipping, which could potentially be more significant, particularly for just-in-time supply chains. Additional labor costs averaged about $11 per container over the duration of the disruption, and these costs are borne by the terminal operator (often a subsidiary of the carrier). The total cost of the disruption—about $28 per container—reflects a price increase of several percent. The cumulative disruption cost was conservatively calculated to be about $1.4M. Recall that this estimate does not include telecommunications workarounds (such as using couriers for hand delivery of documents), the full cost of export dwell times, or the impacts of supply chain disruptions.

Conclusions and Future Extensions

This paper presented an example of the work that is currently under way at the National Infrastructure Simulation and Analysis Center (NISAC), a U.S. Department of Homeland Security program with Sandia National Laboratories and Los Alamos National Laboratory as technical partners. A goal of the work is to develop tools that can be used by federal, state, and local government agencies to improve the security, resiliency, and long-term economic viability of the infrastructures that are vital to the U.S. economy. The port simulator and the N-SMART simulator are examples of some of the tools being developed by NISAC that will ultimately provide powerful analysis capability to the key decision-makers that need the information most. These simulators were showcased in Spring 2003 for federal, state, and local government representatives, city and port planners, port operators, and key industry leaders whose businesses rely on viable port operations. After experiencing "hands on" the power of the simulators, they were eager to adopt the use of these tools in optimizing the processes and security of their operations.

Sandia National Laboratories and Bell Laboratories are continuing to develop inter-infrastructure simulation models, extending them to include both wireline and wireless voice and data communications across public and private networks. This first instance of modeling ports in combination with communications disruptions appears to be a reasonable surrogate for what might happen to many industries that rely heavily on telecommunications. Furthermore, some of those industries may suffer doubly because of supply chain disruptions caused by disruptions to the port. This effort is expected to continue with analysis of information and telecommunication networks interactions with other critical infrastructures, specifically the agriculture, food, water, public health, emergency services, government, defense industrial base, energy, transportation, banking and finance, chemicals industry and hazardous materials, and postal and shipping infrastructures.

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