Impact of the 2001 World Trade Center Attack on Critical Interdependent Infrastructures*

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Abstract - *This paper investigates the impact of the 2001 World Trade Center attack on critical infrastructure systems in the New York City metropolitan area. Of particular interest are the physical or logical connections—also known as interdependencies—among these systems, and the results of disruptions associated with the attack on them. Prior research on infrastructure interdependence has concentrated on modeling the consequences of interdependencies among impacted infrastructure systems. This paper catalogues and analyzes reports of impacts to interdependent infrastructure systems associated with the 2001 World Trade Center attack. The results suggest that there were impacts to various types of interdependencies among nearly all critical infrastructure systems. Moreover, impacts continued to be reported throughout the one hundred day period following the attack. The paper concludes with a discussion of possible strategies for improving understanding of infrastructure interdependencies and for managing them during an emergency response.*

Keywords: critical infrastructures, interdependence

1 Introduction

Critical infrastructure systems provide services whose operations are crucial for the economic well-being and security of a nation and its citizens. It is therefore of vital importance that their services not be degraded, whether by willful acts such as terrorism or by natural or random events such as earthquakes, design flaws or human error [11]. Yet infrastructure systems and the organizations that manage them are now recognized as components of highly-coupled systems that increasingly rely on one another in order to deliver key services.

In the United States, a recent report of the President's Commission of Critical Infrastructure Protection [7] identified and discussed the need to protect eight critical infrastructure systems: emergency services; transportation; information and communications; electric power; banking and finance; gas and oil production, storage and transportation; water supply; and government. Subsequent work on critical infrastructure systems has emphasized the need to conceive of these infrastructures as elements of "systems of systems." In other words, the physical or logical connections among these systems with each other mean they must work in concert to provide key services. Infrastructures in such a system of systems should be regarded as *interdependent*.

This research is intended to improve understanding of the risks entailed in the management of interdependent critical infrastructure systems following sudden onset, disruptive events. Previous work on the management of infrastructure interdependencies has focused largely on mathematical approaches to modeling interdependent infrastructure systems [2, 12]. The present research extends the scope of these inquiries by examining the nature and extent of disruptions to interdependent critical infrastructures following the 2001 World Trade Center attack as they were reported in the national press. By illustrating the scope and variety of interdependencies as observed in an actual event, this research adds to the range of problems that analytic- or simulation-based methods may be asked to address.

The paper proceeds as follows. A brief historical overview (Section 2) provides the context for understanding how infrastructure systems came to be interdependent. Formal definitions of various types of interdependence are then presented (Section 3). These definitions are then used (Section 3) to identify impacts to infrastructure systems and to the interdependencies among them in the New York City metropolitan area as reported in articles from the *New York Times* from 12 September 2001 to 12 December 2001. The paper concludes with a discussion of possible strategies for improving understanding of infrastructure interdependencies and for managing them during an emergency response.

2 Historical Overview

The earliest records of the construction and use of infrastructure systems in the United States of America

(U.S.) show that interdependency has long been designed into them. Recent rapid improvements in technology have, however, enabled greater degrees of interdependency and, consequently, increased risks associated with the propagation of disruptions across infrastructure systems. A brief consideration of the trajectory of this change is used here to frame the discussion of impacts associated with sudden-onset disasters.

For purposes of this discussion, it is useful to divide infrastructure as belonging either to civil infrastructure systems or to service systems. Civil infrastructure systems include infrastructures such as water, transportation and power. They rely on a constructed system in order to provide services, such as power delivery, voice and data transmission. Typically, each system's components can only be used to support services of their respective group (communications lines cannot be used for energy transmission and vice versa; water system pipelines are not readily available for energy products such as gas or fuel). Service systems include infrastructures such as banking, finance and emergency services. Service systems can only provide a service by relying to a large extent on the civil infrastructures.

Each of the civil infrastructure systems evolved separately. Road, water and sewer systems date back nearly 6,000 years in world history [3] and have been essential in providing water to settled areas, roads for the movement of goods and people between settled areas, and avenues for the removal of waste to contribute to public health [10]. The development of any of these civil infrastructure systems has typically been made possible by the system becoming reliant on some other system [4].

Transportation is the oldest U.S. infrastructure [3]. Horse paths and wagon trails led to rail systems stretching across the country, connecting, and in some cases creating, cities. Within those cities, the installation of rails led to the replacement of horse-drawn omnibuses with horse-drawn trolleys [9] which were later electrified as the power systems grew. Subways appeared at the end of the nineteenth century. The twentieth century brought cars, trucks, and buses, which all necessitated growth of the road infrastructure and required energy systems in order to provide their service.

Gas was the first energy infrastructure. Small local coal and gas plants produced the gas which was distributed via a dedicated piping system to homes and businesses [4, 10]. Electricity followed with its system of generators, transmission and delivery networks [4, 10]. Natural gas and petroleum pipelines and refineries complete the set of energy systems. The pipeline systems relied on power for compressors and on communications for data acquisition and control systems.

The growth of cities led to the need for increased water supplies. Systems to provide gravity-fed or pumped water from lakes, ponds and springs were followed by dams, reservoirs and the piping systems necessary to deliver the water where needed [1, 4, 10]. Distribution networks then delivered the water to where it was needed, relying on power for pumps when gravity feed was not sufficient.

Telecommunications, the latest infrastructure system, began with the telegraph. Telephones followed, evolving from operators and local switchboards to worldwide networks with high-speed digital switches [10]. Internet and wireless technologies have become the newest additions to the telecommunications infrastructure.

Early power, water, sewer and gas systems were designed to serve local populaces. With the exception of roads, all such systems were initially privately owned, with customers paying for the service they received. Government at the state and federal levels took responsibility for the road systems, using taxes and tolls to build and maintain them for the common good [10].

Each agency or company that owned or managed these systems developed its own control and monitoring systems. As infrastructure systems grew to cover larger regions and to serve growing populations, more advanced monitoring was required. Greater efficiency was gained in systems such as communications when computers began to aid operators in decision making and control. Expanded reliance on other systems increased interdependence.

3 Establishing Terminology

Recent research on infrastructure interdependence has been mainly technical and not historical or descriptive in nature. By enriching the history of infrastructure interdependence, researchers can better assess both designed interdependencies and those that may emerge or evolve over time. The occurrence of events that impact infrastructures can present numerous opportunities for developing such descriptions. Terminologies of types of infrastructures and infrastructure interdependencies [12] are available and are briefly reviewed in this section as a prelude to their use in the remainder of the paper.

An infrastructure is a framework of interdependent networks and systems, comprised of identifiable industries, institutions (including people and procedures), distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of a nation, the smooth functioning of government, and society as a whole. More formally, an *infrastructure* is a linked set of physical components with associated activities; activities are tasks necessary to operate physical components of the infrastructure; and physical components are the man-made parts of an infrastructure. For example, in the transportation infrastructure, one activity is routing subway trains. Physical components acted upon during this activity could include switching mechanisms and electrical signals.

In the United States, the President's Commission on Critical Infrastructure Protection [7] defined eight infrastructures as critical. The infrastructures, and the abbreviations used for them in this paper, are shown in Table 1.

Table 1. U.S. Critical Infrastructures

Full Name	*Abbreviated Name*
Banking and Finance	Banking
Electric Power	Power
Emergency Services	Emergency
Gas and Oil Production, Storage and Transportation	Gas/Oil
Government Services	Government
Information and Communications	Telecom
Transportation	Transportation
Water Supply Systems	Water

A service is something made available by one or more infrastructures for use or consumption. Services may be used by people or by other infrastructures; they are provided in order to meet a real or perceived need. An example of a service is public transportation. In order to provide this service, many infrastructures are utilized. When the service is provided by the subway, for example, a transit authority may be the responsible agency.

A *disruption* to service occurs when one or more of the physical components and one or more of the associated activities of an infrastructure cannot operate at prescribed levels. Disruption may or may not result in service degradation. When service itself cannot be provided at its prescribed level, a disrupted infrastructure is said to be directly involved. Indirect involvement of one infrastructure can happen if it has a dependent or interdependent relationship with another disrupted infrastructure. An infrastructure is *interdependent* on one or more other infrastructures if any of the following four conditions hold:

- *Input*: the infrastructure requires as input one or more services from another infrastructure in order to provide a service;
- *Shared*: some physical components and/or activities of the infrastructure used in providing the service are shared with one or more other infrastructures;
- *Exclusive-or*: either the infrastructure or some other infrastructure (but not both) can be in use during provision of the service;
- *Co-located*: two or more infrastructures' physical components or activities are co-located within a prescribed geographical region.

The following analysis illustrates the extent of disruptions to infrastructures and infrastructure interdependencies following the 2001 World Trade Center attack.

4 Post-WTC Disruptions

The 2001 World Trade Center (WTC) attack led to widespread utility outages in the lower Manhattan area. Figure 1 illustrates utility outages on 19 September 2001, suggesting that numerous disruptions to services provided by critical infrastructures resulted from the attack.

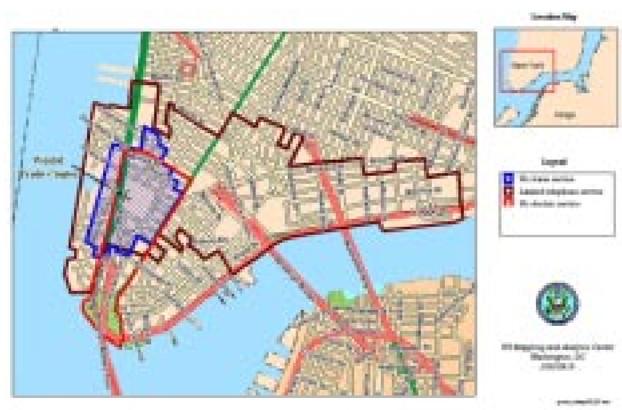

Figure 1. Extent of Utility Outages: 19 September 2001

To gain a clearer picture of the nature and duration of these disruptions, instances of disruption to critical infrastructures in the borough of Manhattan are here summarized by drawing upon reports published in the *New York Times* Metro edition for the period 12 September 2001 to 12 December 2001, a period which is intended to approximate the length of the response phase.

Independent coders were provided with hard copy of all the above issues of the *New York Times*. They cataloged (i) which of the eight infrastructures shown in Table 1 were impacted by the attack and (ii) whether or not each impacted infrastructure was involved, either directly or indirectly (i.e., as a result of interdependency with a directly impacted infrastructure), in an interdependency. The type of interdependency, if present, was noted; if no interdependency was present, a category of None was used. Duplicate incidents were eliminated.

4.1 Impacts to Infrastructure Systems

Incidents involving disruptions to critical infrastructure systems were extensively reported during the study period. A graphical chart of the daily totals by infrastructure over each day in Week 1 is shown in Figure 2, which suggests a gradual decline in the number of reported disruptions as the week progressed. Reports of disruptions to Emergency, Transportation, Telecom and Government infrastructures declined during Week 1, while those to Banking fluctuated, perhaps reflecting an ongoing concern with the impact of WTC-related disruptions on the health and stability of world banking and financial markets. Disruptions to Power also fluctuated, though there were relatively few reports of disruptions (despite widespread power outages in lower Manhattan). No disruptions were reported for Water and few for Gas/Oil.

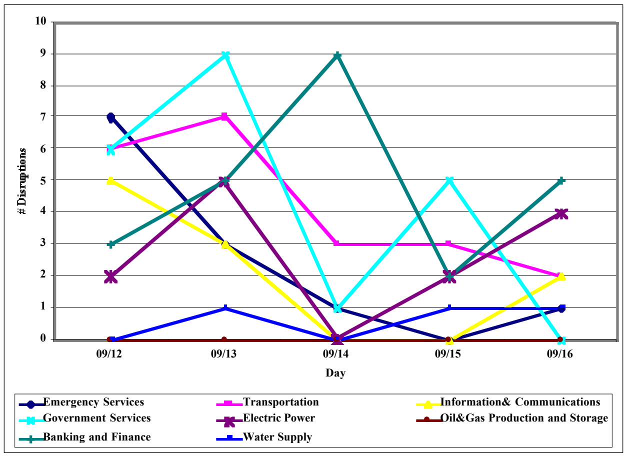

Figure 2. Infrastructure Disruptions (Week 1)

A separate analysis of variation in the number of disruptions per day shows that overall variability in the number of reported incidents is relatively low for Gas/Oil and Water and relatively high for Emergency and Government.

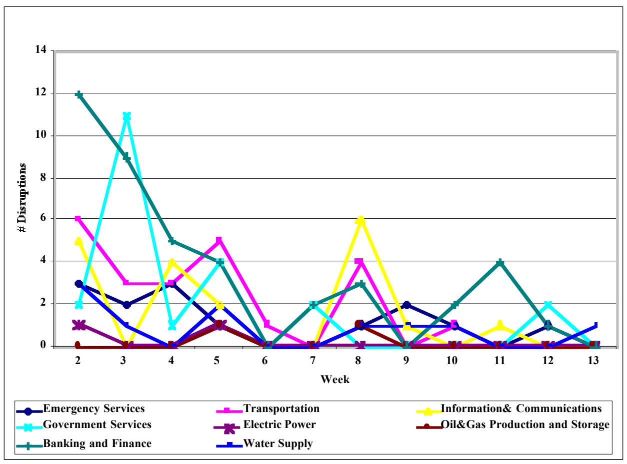

Figure 3. Infrastructure Disruptions (Weeks 2-13)

Disruptions to infrastructures continued to be reported for the remainder of the study period (i.e., Weeks 2-13). A graphical chart of the daily totals by infrastructure for each of Weeks 2 through 13 is shown in Figure 3, which suggests an overall decline in disruptions for all infrastructures except Telecom, although occasional spikes in the data are present. A separate analysis shows that the mean number of disruptions per week for Weeks 2-13 decreased or stayed the same for all infrastructures except Gas/Oil and Water. Week-to-week variability in Weeks 2-13 seemed not to differ appreciably from the day-to-day variability exhibited in Week 1, suggesting that Weeks 2-13 were less turbulent than Week 1. (An average of less than one disruption per day was reported in Weeks 2-13 for each infrastructure systems. Consequently, the standard deviation across days is less than one for all infrastructure systems except Government and Banking—which had respective standard deviations of 1.1 and 1.3.)

Table 2 summarizes the data presented above in three ways. The *Total* section shows the total number of disruptions reported for each infrastructure in Week 1, Weeks 2-13 and Weeks 1-13. For Emergency and Telecom, the number of reported disruptions in Week 1 was approximately equal to the total for the remainder of the study period. For Transportation, Government and Banking, the number of disruptions in Week 1 greatly exceeded that in the remainder of the study period. For Power, Gas/Oil and Water, more disruptions were reported in Weeks 2-13 than in Week 1.

The *%Overall Total* section shows the percentage of disruptions for a particular period associated with each infrastructure system. In Week 1, for example, there were 130 disruptions reported, 16 (or 12%) of which were to Emergency. For Week 1, the percentages for all infrastructures except Gas/Oil and Water were approximately equal (about 14%); those for Gas/Oil and Water were much lower (2% and 5% respectively). The situation changed in Weeks 2-13, when Power, Gas/Oil and Water were approximately equal (about 15%), while the percentages for the remaining infrastructures were each about 7%. For the entire study period, then, the percentages for the various infrastructures were approximately equal (Telecom being the lowest at 9%, the others being about 12%).

Table 2. Summary: Infrastructure Disruptions (by Week)

	Emerg.	Transp.	Telecom	Govt.
Total				
1	16	21	15	22
2-13	16	11	12	14
1-13	32	32	27	36
%Overall Total				
1	12%	16%	12%	17%
2-13	9%	6%	7%	8%
1-13	11%	11%	9%	12%

	Power	Oil/Gas	Banking	Water
Total				
1	14	2	33	7
2-13	25	30	10	27
1-13	39	32	43	34
%Overall Total				
1	11%	2%	25%	5%
2-13	14%	17%	6%	16%
1-13	13%	11%	14%	11%

In the next section, the impacts to interdependencies among these eight infrastructure systems are examined.

4.2 Impacts on Interdependencies

Impacts to interdependencies were identified and classified using the definitions described given above as applied to the same set of *New York Times* issues. Total reported disruptions by type of interdependency are shown for Week 1 in Table 3 and for Weeks 2-13 in Table 4. Instances of all types of interdependence except Shared were found for both periods.

In Week 1, co-location (Coloc.) was the predominant type of interdependence, followed by Input and exclusive-or (XOR). The large proportion of instances of Co-location interdependency may reflect the consequences of the impact at Ground Zero.

Table 3. Interdependency Disruptions (Week 1)

Date	Input	Coloc.	XOR	Total
12 Sep.	11	8	0	19
13 Sep.	0	10	0	10
14 Sep.	0	2	1	3
15 Sep.	2	6	0	8
16 Sep.	6	10	1	17
Total	*19*	*36*	*2*	*56*

For the remainder of the study period, Input and Co-location interdependencies were approximately equal. The frequency of reported disruptions involving interdependencies declined over time.

Table 4. Interdependency Disruptions (Weeks 2-13)

Week	Input	Coloc.	XOR	Total
2	8	6	0	14
3	6	7	0	13
4	6	0	0	6
5	0	4	0	4
6	0	0	0	0
7	0	0	0	0
8	6	4	0	10
9	0	2	0	2
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
Total	*26*	*23*	*0*	*49*

Because each type of interdependency involves at least two infrastructure systems, there are (8×7)/2=28 possible pairwise connections between the infrastructure systems considered in this study. For simplicity, when an interdependency involved three or more infrastructures, all possible pairs were tallied. So, if an interdependency involved 3 infrastructures, three pairs were counted. A tabulation was made of all pairs of infrastructures involved in interdependency relationships. According to Figure 4, which summarizes the results, ten infrastructure pairs were not involved in any disrupted interdependencies, six pairs were involved in one disrupted interdependency each, etc. So, 18 of the 28 pairs that could have been involved in disrupted interdependencies actually were. The median number of impacts on a pair of infrastructure systems was two.

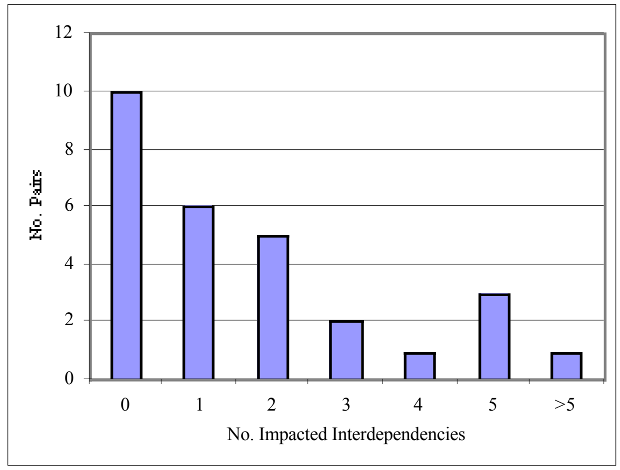

Figure 4. Impacted Interdependencies (All Infr. Pairs)

A separate analysis shows that Telecom and Power had more incidents involving interdependencies than those involving only the infrastructure itself. The Transportation, Government, Oil/Gas, Water and Banking infrastructures had fewer incidents that identified interdependencies than those that did not. Emergency, which often depends on Transportation, had an almost equal number of incidents involving and not involving interdependencies. It may be that infrastructures like Government and Banking have a greater global impact than civil infrastructures, which by their very definition are local.

5 Discussion

The preceding analysis expands prior research on critical infrastructure interdependence by considering the extent and pattern of reported disruptions following the 2001 World Trade Center attack. The results suggest that reported disruptions were approximately equally distributed across the eight critical infrastructures when considering the study period as a whole. In considering the initial one-week period in comparison to Weeks 2 through 13, however, different patterns emerge. Some infrastructures experienced more disruptions in Week 1 and less in the remainder; for others it was the reverse; for others, the number of disruptions in Week 1 was approximately equal to the total number in Weeks 2 through 13.

Impacts involving Co-location and Input interdependence were most common, with Co-location dominating in Week 1, but with Co-location and Input approximately equal in Weeks 2 through 13. Impacts to interdependencies were found in most combinations of infrastructures (e.g., Telecom and Power). Impacts to Telecom and Power more often involved interdependence than not.

6 Conclusions

Since the September 11, 2001 attacks, there have been numerous reports describing the vulnerabilities in and among U.S. infrastructure systems, as well as extensions and modifications of the original set of critical infrastructures [5]. Yet for a variety of technical and organizational reasons, the management of interdependencies remains a challenge [6].

Critical infrastructures are managed by a variety of organizations—such as government agencies, private companies and not-for-profit authorities—whose goals are to provide services as effectively and safely as possible. Interdependencies that become evident following an extreme event must themselves be managed in order to restore the flow of services, yet different interdependencies may require different risk management strategies. For example, an exclusive-or interdependence means that two or more services must compete for that particular infrastructure: this may entail identifying decision makers and determining the decision-making protocol.

In a disaster, responding personnel must be apprised of designed interdependencies and given information on the impact of the disruption on them. Without a requirement for managers of different infrastructures to collaborate and coordinate during routine operations, it may be necessary to establish an outside agency (such as an Emergency Operations Centers) that will do so during disaster response and recovery. Similarly, emergency response plans and training exercises should plan for the need to coordinate response and restoration activities among managers of interdependent infrastructures.

The results of this research reinforce the view that critical infrastructure systems should be viewed as a "system of systems" [8]. To maintain and embrace a quality of life, both in normal times and in extraordinary situations, it will be necessary to continue in developing detailed understanding of the theoretical and observed behavior of interdependent critical infrastructures.

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