

Impacts of the 2001 World Trade Center Attack on New York City Critical Infrastructures

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Abstract: This study investigates impacts 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 impacts of the attack on them. This study extends knowledge about the behavior of complex and interdependent infrastructures systems following a significant disruption. The results depict impact to all infrastructure systems as a result of the attack, with disruptions reported throughout the 3 month study period. Approximately 20% of these disruptions involved interdependencies, and a majority of infrastructure systems were involved in at least one interdependency. The results therefore suggest that interdependence is a pervasive condition of New York City's critical infrastructures. Accordingly, approaches to planning for and managing infrastructure-related disruptions, particularly those involving interdependency, are discussed.

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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 these services not be disrupted, whether by willful acts such as terrorism or by natural or random events such as earthquakes, design flaws or human error. Yet critical infrastructure systems and the organizations that manage them are now recognized as components of highly coupled and complex systems that increasingly rely on one another in order to deliver key services. The management of such interdependent systems creates a range of policy-, technology-, and society-related challenges.

This paper addresses the need to understand the behavior of interdependent critical infrastructure systems, particularly when they are disrupted by willful, natural, or random events. The approach is to investigate how one system—the critical infrastructures of New York City—was impacted by the 2001 World Trade Center attack. The objectives are first to uncover patterns of disruptions associated with the attack, and then to consider the implications of these results for the management of interdependent critical infrastructures. This approach complements prior studies by using data from the field to describe the behavior of interdependent infrastructures.

The paper proceeds as follows. Background work is first

considered, and is used to establish terminology used in the remainder of the study. A description of the methodology used in identifying and describing infrastructure-related disruption is presented and applied to reports of disruptions in New York City for the period September 12, 2001–December 12, 2001. The paper concludes with a discussion of the implications of this work for the management of critical infrastructure systems.

Background

An infrastructure is a framework of interdependent networks and systems, comprised of identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of government and society. 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 built parts of an infrastructure (Peerenboom et al. 2001; Wallace et al. 2003). For example, in the transportation infrastructure, one activity is routing subway trains, which requires manipulating physical components such as switching mechanisms and electrical signals.

Critical Infrastructures

An early report published in the United States (President's Commission on Critical Infrastructure Protection 1997) identifies and defines eight infrastructures that support the "life support systems" of the country and are therefore regarded as critical (see Government Accountability Office 2004 for a brief review of subsequent modifications to these definitions:

1. *Emergency services:* An infrastructure characterized by medical, police, fire and rescue systems, and personnel that are called upon when an individual or community is responding to emergencies. These services are typically provided at the local level (county or metropolitan area). In addition,

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state and federal response plans define emergency support functions to assist in response and recovery. Emergency services include fire, police, emergency medical, rescue, and the like.

2. *Transportation*: An infrastructure characterized by the physical distribution system critical to supporting the nation's security and economic well being, including the national airspace system, airlines, aircraft, and airports; roads and highways, trucking and personal vehicles; ports and waterways and the vessels operating thereon; mass transit, both rail and bus; freight and long haul passenger rail; and delivery services.
3. *Information and communications*: An infrastructure characterized by computing and telecommunications equipment, software, processes and people who support: (1) the processing, storage, and transmission of data and information; or (2) the processes and people that convert data into information and information into knowledge, and the data and information themselves.
4. *Electric power*: An infrastructure characterized by generation stations, transmission, and distribution networks that create and supply electricity to end users so that they achieve and maintain nominal functionality of residential, business, and government sectors, including the transportation and storage of fuel essential to this system.
5. *Banking and finance*: An infrastructure characterized by entities, such as retail and commercial organizations, investment institutions, exchange boards, trading houses, and reserve systems, as well as associated operational organizations, government operations, and support activities that are involved in all manner of monetary transactions, including its storage for saving purposes, its investment for income purposes, its exchange for payment purposes, and its disbursement in the form of loans and other financial instruments. This infrastructure includes banks, nonbank financial services companies, payments systems, investment and mutual fund companies, securities and commodities exchanges, and the like.
6. *Gas and oil production, storage, and transportation*: An infrastructure characterized by production and holding facilities for natural gas, crude and refined petroleum, and petroleum-derived fuels, as well as the refining and processing facilities for these fuels and the pipelines, ships, trucks, and rail systems that transport these commodities from their source to systems that are dependent upon gas and/or oil.
7. *Water supply systems*: An infrastructure comprised of the sources of water, reservoirs and holding facilities, aqueducts and other transport systems, filtration, cleaning and treatment systems, pipelines, cooling systems, and other delivery mechanisms that provide for domestic and industrial applications, including systems for dealing with water runoff, waste water, and fire fighting.
8. *Government services*: An infrastructure comprised of levels of Federal, state, and local governments which provide essential services to the public.

As suggested by the above definitions, one or many infrastructures can provide *services*, defined as something made available by the infrastructure for use or consumption. Services may be used by people or by other infrastructures, and are provided in order to meet a real or perceived need. An example of a service is public mass transit, the provision of which requires other infrastructures, such as electric power and information and communications.

For a variety of reasons, the evolution of infrastructure systems in the United States has led to their becoming interdependent (Grigg 2001; Tarr and Dupuy 1988): that is, because they share physical space or physical or logical connections with each other, they must work in concert to provide key services. More formally, for the present study, an infrastructure is said to be *interdependent* on one or more other infrastructures if any of the following four conditions hold (Wallace et al. 2003):

1. *Input*: The infrastructure requires as input one or more services from another infrastructure in order to provide a service. As an example, services from electric power are required to run various parts of the transportation infrastructure.
2. *Shared*: Some physical components and/or activities of the infrastructure used in providing the service are shared with one or more other infrastructures. As an example, roadways may be used by both electric power and emergency services.
3. *Exclusive-or*: Either one infrastructure or another (but not both) can be in use during provision of the service. As an example, policy may dictate that a portable power generator be used either by emergency services or telecommunications but not both.
4. *Colocation*: Two or more infrastructures' physical components or activities are colocated within a prescribed geographical region. As an example, information and communications and banking and finance may have components that are located in the same building. The prescribed geographic region may also be larger, such as a city block, or smaller, such as the floor of a building.

The presence of one or more of these four conditions implies that an impact on one infrastructure system is also an impact on another infrastructure system. If an infrastructure is not interdependent, it is said to be *independent*.

Disruptions to Services Provided by Critical Infrastructures

The nature and extent of susceptibility of critical infrastructures to disruption are key concerns in preserving a nation's security, economy, and overall well being (Amin 2002; Grigg 2001; Pikus 2003; Rinaldi 2004; Zimmerman 2005). It is therefore appropriate to consider how willful acts or random events (i.e., *incidents*) may interrupt the flow of services provided by critical infrastructures. A *disruption* to a service is said to occur when one or more of the physical components and one or more of the associated activities of an infrastructure cannot operate at prescribed levels. If the disruption results in an inability to meet demand, then the service is said to be *degraded*.

Studying Interdependent Systems

As discussed previously, an important aspect of infrastructure systems is their behavior following a disaster. The view adopted here is that a holistic, system-oriented approach should be taken in trying to determine the behavior of human- and technology-centered infrastructures (Little 2004). Field studies are useful in this regard, both to describe historical incidents (O'Rourke et al. 2003) and to develop a scope of inquiry for further investigations (Gilbert et al. 2003; Luijff and Klaver 2004). Field studies may, for example, provide data for later use in laboratory studies (Mendonça et al. 2003) and computer simulations (Haimes and Horowitz 2004; Rinaldi 2004), and may also contribute more broadly to vulnerability analyses (Gilbert et al. 2003). Yet oppor-

Table 1. Incident Identification

Index	Month	Day	Year	Section	Page	Article title	Indicator
1	09	12	2001	A	2	Rescue...	A
2	09	12	2001	A	2	Rescue...	B
3	09	12	2001	A	2	Rescue...	C
4	09	12	2001	A	7	Trying...	A

tunities for conducting field studies of disaster are limited (Mileti 1999). The U.S. National Science Foundation, on its own and through the University of Colorado's Quick Response Grants program, has continued to make funds available to support rapid deployment of teams to study human response to disaster. The lack of experimental control inherent in field studies suggests that an exploratory, case study-based approach (Yin 1993, 1994) is appropriate (Quarantelli 1997). Such an approach is taken in the present study, as described next.

Study Design

In order to assess the impacts of the 2001 World Trade Center attack on critical infrastructures in New York City, the following three questions are posed:

1. What *incidents* were reported that led to disruptions in critical infrastructures?
2. What *disruptions* to the services provided by critical infrastructures resulted from these incidents? and
3. What *interdependencies* among disrupted critical infrastructures were impacted?

The methodology and analytic approach used in addressing these questions are presented next.

Methodology

Instances of disruption to services provided by critical infrastructures in New York City are identified using published reports for the period September 12, 2001–December 12, 2001, which closely approximates the length of the response and recovery phases to the World Trade Center (WTC) attack. A search for publicly available sources that published in-depth and timely reports of infrastructure-related disruptions was first conducted, yielding two candidate sources, *The Wall Street Journal* and *The New York Times*. Coverage by *The Wall Street Journal* was limited mainly to impacts on the banking and finance infrastructure, and for this reason it was not used. In contrast, coverage by *The New York Times* appeared to include descriptions of impacts to many critical infrastructures, and for this reason was used as the source. It should also be noted that the *New York Times'* coverage of the attack and its aftermath was recognized with Pulitzer Prizes in the categories of explanatory reporting, breaking news photography, and public service.

Table 2. Impacted Infrastructure Systems

Index	Emergency services	Transportation	Information and communications	Government services	Electric power	Oil and gas production and storage	Banking and finance	Water supply
1	1	—	—	—	—	—	—	—
2	1	—	—	—	—	—	—	—
3	1	1	—	—	—	—	—	—

Table 3. Involvement of Interdependencies

Index	Input	Shared	Exclusive-or (XOR)	Colocation	None
1	—	—	—	—	1
2	—	—	—	—	1
3	2,1	—	—	—	—
4	1,3,4	—	—	1,4	3

A set of instructions for identifying and classifying reported incidents, disruptions, and interdependencies was first developed, using the definitions described previously. Two individuals were then trained in using these instructions so that they produced consistent results from both individuals on a test data set. They were next provided with hard copies of the *New York Times* metropolitan edition and worked independently to implement the instructions. One individual coded the entire set of articles for the study period; the other coded a random sample of ten percent of the daily issues so that the coders' degree of agreement could be observed. The results of the coding were entered into a computer database.

The first four records from the database are reproduced in Tables 1–3. Table 1 shows the identifying information: an Index field that is used to identify each record uniquely; the date fields (month, day, and year); the section and page number fields; and the title of the article, which is here truncated. An indicator variable (Indicator) is used in order to tally the number of distinct incidents reported in a given article, since many articles reported on more than one incident. For example, the first article (“Rescue . . .”) described three incidents (A, B, C). The value in the Index field uniquely identifies each incident for later analysis (e.g., Index 1 pertains to the first incident reported in the article entitled “Rescue...”). For convenience, the value of the Index field is repeated in Tables 2 and 3, below. Finally, it should be noted that all the results were screened in order to eliminate duplicates (as occurred when two articles reported on the same event).

Table 2 shows the number of disruptions reported in each incident for each of the various infrastructures (a blank entry means that no disruption was reported for that infrastructure). Incidents A (Index 1) and B (Index 2) involved emergency services; Incident C (Index 3) involved emergency services and transportation.

Table 3 shows the recording of disruptions as input, shared, exclusive-or (XOR), colocation, or none, where none shows that the impact was confined to a single infrastructure. The number in a cell corresponds to the number shown above the infrastructures listed in Table 2. So, for Index 3, transportation and emergency services were involved in an input interdependency.

Analytic Approach

The analysis is divided into three sections, one for each of the three research questions given previously. Question 1 is used to



Fig. 1. Infrastructure interdependency

identify incidents that disrupted critical infrastructures. Question 2 details which infrastructure systems were disrupted, thus providing an assessment of the impact of the attacks on them. Question 3 explores patterns in interdependencies that were impacted by these disruptions.

Results

The WTC attack led to immediate widespread utility outages in the lower Manhattan area. Examination of the written and photographic record of the attack suggests that infrastructure interdependencies impacted the flow of critical services in various ways (O'Rourke et al. 2003), including changes both in the built environment and in human systems (Faber et al. 2004; Kelly and Stark 2002; Zimmerman 2003). Fig. 1 shows a consequence of the towers' collapse to components of the transportation and emergency services critical infrastructures. Similar observations may be made about the telecommunications, power, and water infrastructures in Manhattan, N.Y., all of which were heavily impacted by the attack (O'Rourke et al. 2003; Zimmerman 2003). These changes in the built environment created challenges for those seeking to collect information about the current status of these infrastructures in order to plan appropriate response activities. Taken together, the results of prior work on the attack illustrate disruption to the physical environment, the need for accurate information about this newly perturbed environment, and the consequences of disruption to the services provided by critical infrastructures.

In the material to follow, an analysis is presented of disruptions to New York City critical infrastructures that were induced by the WTC attack. The infrastructures (with abbreviations given in parentheses) are those described previously (President's Commission on Critical Infrastructure Protection 1997): *emergency services*; *transportation*; information and communications (*telecom*); electric power (*power*); banking and finance (*banking*); gas and oil production, storage, and transportation (*oil and gas*); water supply systems (*water*); and *government services*. The following examples illustrate disruptions to interdependencies among these infrastructures.

1. *Input*: At 10:20 a.m. on September 11, 2001, following the collapse of the first World Trade Center tower, transit authorities decided to suspend all subway service, issuing an

Table 4. Number of Incidents: Week 1

Day	Total
September 12	24
September 13	25
September 14	11
September 15	11
September 16	10
Total	81

order to send all trains to their yards or to secure them in the tunnels. Five minutes earlier, several subway lines were left without alternating current, which supplies power to the trains through the third rails, and without direct current, which runs the signals. Officials did not know exactly how the power was disrupted. But because of the power loss, the closing of all stations in lower Manhattan and the possibility of further explosions or collapses, "the general consensus was that the best thing to do was discharge all passengers and secure the trains temporarily," a transit authority spokesperson said (Kennedy 2001).

2. *Exclusive-or*: Following the collapse of the WTC towers, financial services were disrupted because employees could not use the streets and sidewalks to travel to work. Some areas in New York's financial district are narrow and congested even under normal circumstances; debris and vehicle and human traffic made them more so following the collapse (Berenson 2001).
3. *Colocation*: There were numerous examples of both power lines and fiber optic cables being located in the same manhole, thus creating the need for organizations responsible for these infrastructures would have to coordinate shared use of manholes (New York Times editorial staff 2001).

Reported Incidents

Reported incidents are those incidents which impacted one or more critical infrastructures. Because the majority of disruptions occurred during the first week following the attack, data for addressing Question 1 are presented from three perspectives: disruptions during Week 1, disruptions during Weeks 2–13, and disruptions for the entire study period.

Table 4 shows a large number of reported disruptions in Week 1 relative to subsequent weeks, as shown in Table 5.

Table 5. Number of Incidents: Weeks 2–13

Week	Total
2	26
3	23
4	15
5	15
6	1
7	4
8	13
9	3
10	5
11	5
12	4
13	1
Total	115

Table 6. Disruptions to Critical Infrastructure Services: Week 1

Day	Emergency services	Transportation	Telecommunications	Government services	Power	Oil and gas	Banking	Water	Total
September 12	7	6	5	6	2	0	3	0	29
September 13	3	7	3	9	5	0	5	1	33
September 14	1	3	0	1	0	0	9	0	14
September 15	0	3	0	5	2	0	2	1	13
September 16	1	2	2	0	4	0	5	1	15
Mean	2.4	4.2	2	4.2	2.6	0	4.8	0.6	20.8

Weekly totals for Weeks 2–13 decreased appreciably over time (with some exceptions, such as Week 8), so that by Week 13 only one incident was reported. Reported incidents involving critical infrastructures diminished over time, but persisted throughout the study period, resulting in a total of 196 incidents.

Disruptions to Services Provided by Critical Infrastructures

Disruptions to services provided by critical infrastructures were next assessed. As shown in Table 6, most reported disruptions in Week 1 were to transportation, government services, and banking. Reports of disruptions to four infrastructures (emergency services, transportation, telecom, and government services) declined overall 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 domestic and international financial markets. Disruptions to government services and power also fluctuated, while no disruptions were reported for oil and gas and few for water. In total, 104 disruptions were reported in Week 1. The data are summarized graphically in Fig. 2.

Disruptions continued to be reported in Weeks 2–13, as shown in Table 7 and summarized graphically in Fig. 3. An overall decline in disruptions is evident for all infrastructures except banking, and to some extent emergency services. A test of differences in the mean number of disruptions for each infrastructure per week (i.e., the values in the last row of Table 7) can be obtained using Tukey's multiple comparisons procedure for means (Sachs 1984). This procedure clusters the infrastructures into groups hav-

ing statistically equal means. The results of the procedure are as follows for Weeks 2–13 (at $\alpha=0.05$). The cluster of groups having the higher mean number of disruptions consists of banking, transportation, government, and telecom. The cluster with the lower mean consists of transportation, government, telecom, emergency services, water, power, and oil and gas. So, banking may be said to have a significantly higher mean than emergency services, water, power, and oil and gas, while the values for transportation, government, and telecom are not extreme enough to put them in either the higher or lower cluster.

Disruptions for the entire study period are summarized in Table 8. The *Total* section shows the total number of disruptions reported for each infrastructure in each of the three periods (i.e., Week 1, Weeks 2–13, Weeks 1–13). For emergency services, transportation, and government services, the number of reported disruptions in Week 1 was approximately equal to that in the remainder of the study period. For power, the number of disruptions in Week 1 greatly exceeded that in the remainder of the study period. For telecom, oil and gas, banking, and water, more disruptions were reported in Weeks 2–13 than in Week 1. Table 8 underscores the observation that the WTC attack had a differential impact across infrastructures during the study period. Subsequent reports have investigated impacts of the attack beyond the study period (Centers for Disease Control and Prevention 2002; Government Accountability Office 2005).

To summarize, for the study period as a whole, a large percentage of the total disruptions were to banking. In Week 1, a high percentage of the total disruptions were to transportation and government services. Similarly, in Weeks 2–13, emergency services, water, power, and oil and gas had a low percentage of disruptions relative to other infrastructures. Finally, the total number of disruptions from Week 2 to Week 13 was lower than or approximately equal to the total number in Week 1 for all infrastructures except telecom, oil and gas, banking, and water.

Impacts to Interdependencies

To answer Question 3 (i.e., What interdependencies among disrupted critical infrastructures were impacted?), incidents that resulted in disruptions to critical infrastructures were further classified according to whether or not they involved interdependencies, and if so of what type(s). Recall that a single incident might involve a number of infrastructures, and that infrastructures might be involved in various interdependent or independent relationships. Total reported impacts to interdependencies are shown for Week 1 in Table 9. Instances of all types of interdependence except shared were found, with collocation being predominant, followed by input and XOR. The large proportion of instances of collocation may reflect the consequences of the impact in and around the immediate "Ground Zero" area.

As shown in Table 10, for the remainder of the study period,

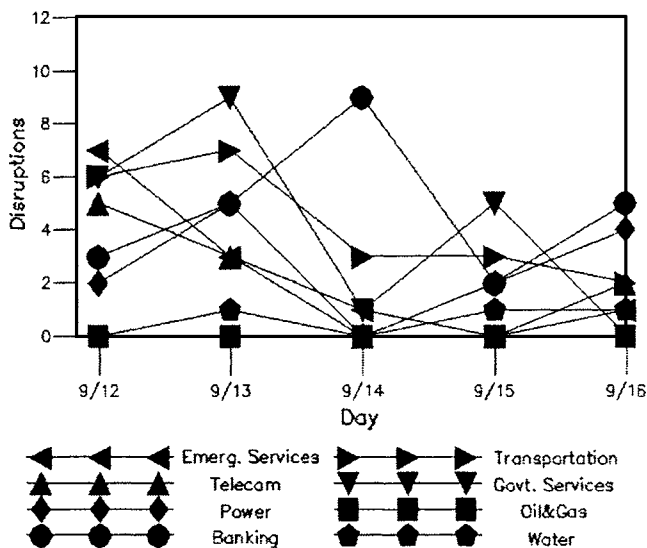
**Fig. 2.** Disruptions: Week 1

Table 7. Disruptions to Critical Infrastructure Services: Weeks 2–13

Week	Emergency services	Transportation	Telecommunications	Government services	Power	Oil and gas	Banking	Water	Total
2	3	6	5	2	1	0	12	3	32
3	2	3	0	11	0	0	9	1	26
4	3	3	4	1	0	0	5	0	16
5	1	5	2	4	1	1	4	2	20
6	0	1	0	0	0	0	0	0	1
7	0	0	0	2	0	0	2	0	4
8	1	4	6	0	0	1	3	1	16
9	2	0	1	0	0	0	0	1	4
10	1	1	0	0	0	0	2	1	5
11	0	0	1	0	0	0	4	0	5
12	1	0	0	2	0	0	1	0	4
13	0	0	0	0	0	0	0	1	1
Mean	1.2	1.9	1.6	1.8	0.2	0.2	3.5	0.8	11.2

impacts to input and colocation interdependencies were approximately equal, with no instances of shared or XOR, and with the frequency of reported impacts declining over time. As in Week 1, most impacts did not involve interdependency. Table 11 summarizes the results for Week 1, Weeks 2–13, and for the entire study period.

To identify any patterns in interdependency relationships, a matrix may be used in which the entry in the (i, j) th cell represents the number of impacts involving interdependency between infrastructure i and infrastructure j ($i \neq j$). The cell values therefore represent disruptions for all possible pairs of infrastructure systems. Table 12 presents the matrix for the current study (note that the matrix is symmetric about the diagonal). As examples, there were two reported impacts to an interdependency between transportation and emergency services, and 11 between banking and telecommunications. Of the 28 possible connections between the various pairs of infrastructure systems, 18 were present at least once, and one pair of connections (between banking and telecom) was found 11 times. A graphical summary of Table 12 is given in Fig. 4, which shows the number of times each cell value appears in Table 12.

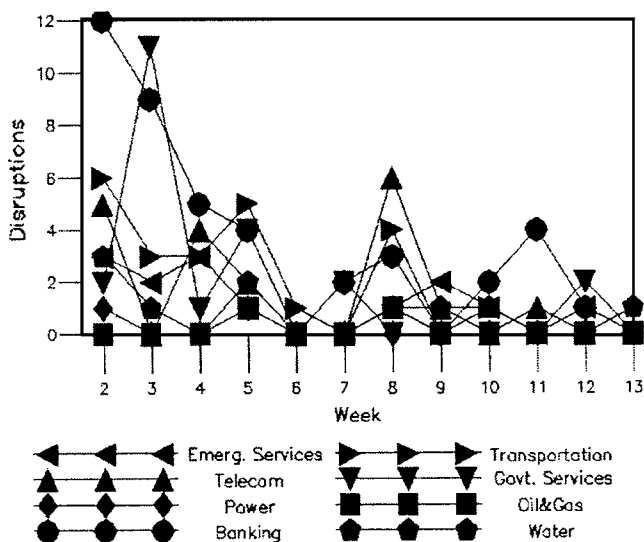


Fig. 3. Disruptions: Weeks 2–13

The data in Table 12 indicate the counts of interdependencies for all pairs of infrastructure, but do not give a measure of association that enables identification of the degree of interdependence (and independence) among the infrastructures. A more formal assessment of the degree of interdependency between infrastructures can be obtained via a test of the correlations among them, in which the null hypothesis is that the correlation between infrastructures X and Y ($X \neq Y$) is zero. The correlation between infrastructures X and Y that is used here is the well-known Pearson's product moment correlation coefficient, denoted Pearson's r (Conover 1999). If an infrastructure was impacted, the value of its variable is set to one; otherwise, it is set to zero. A positive correlation between X and Y arises when values of 1 for X tend to be paired with values of 1 for Y ; a negative correlation arises when values of 0 for X tend to be paired with values of 1 for Y , and vice versa. A value of the correlation coefficient close to 1 or -1 implies association; a value close to zero implies lack of association. Using the sample data in Table 13, the value of Pearson's r is -0.575 .

Results for the complete data set are given in Table 14, which shows the value of two statistics for each (i, j) th cell combination of infrastructure: the value in the upper part of the cell is the estimated Pearson correlation coefficient; the value in the lower part is the p value associated with the test (correlations that are significant at $\alpha=0.05$ or lower are shown in bold).

The results suggest significant correlations among a large proportion (50%) of the infrastructures. Both positive and negative significant correlations were observed, with a range between -0.3256 and 0.1887 . The three significant correlation values for banking were all negative, and involved emergency services, transportation, and government services. It may therefore be inferred that incidents involving banking did not impact these other infrastructures. All infrastructures except emergency services had 3–5 significant correlations with other infrastructures. The three significant correlation values for oil and gas were all positive, and involved transportation, power, and water. It may therefore be inferred that oil and gas is more relevant than banking to overall response and recovery activities. The relative infrequency of significant correlations for emergency services argues for its independence from other infrastructures. The high proportion of significant negative values between the infrastructures of transportation, power, and water and the infrastructures of gov-

Table 8. Summary of Results: Disruptions to Critical Infrastructure Services

Week(s)	Emergency services	Transportation	Telecommunications	Government services	Power	Oil and gas	Banking	Water	Total
1	12	21	10	21	13	0	24	3	104
2–13	14	23	19	22	2	2	42	10	134
1–13	26	44	29	43	15	2	66	13	238

ernment services and banking suggests that disruptions in the first set are not often accompanied by disruptions in the second.

These results highlight the importance of considering both the count data (from Table 12) and the correlation data (from Table 14). As an example banking and telecom had the largest number of interdependencies of all pairs of infrastructure systems. However, there were many cases in which banking and telecom were independent, leading to many occurrences of a value of “1” for one infrastructure and “0” for the other—and hence a negative correlation.

Because different infrastructures may be involved in different types of interdependency relationships, it is worth considering whether there is some relation between infrastructure and interdependency. Table 15—represented graphically in Fig. 5—shows all disruptions to the infrastructures, both those that involved interdependency and those that did not. (Note that the number of impacts to an interdependency is equal to the number of infrastructures involved in the interdependency, and that some disruptions may have involved multiple infrastructures.) An exploratory test on the statistical independence of the columns (infrastructure) and the first three rows (interdependency) may be performed (Conover 1999), in which the null hypothesis is that the rows and columns are independent. At a level of $\alpha=0.05$, the null hypothesis cannot be rejected, leading to the conclusion that infrastructure and interdependency are not dependent. So, for this case, the type of infrastructure impacted does not imply what type of interdependency was likely to have been involved.

In summary, 46 disruptions involved interdependency and 169 did not. Input, colocation, and XOR interdependencies were found, with colocation occurring most frequently, while shared interdependency was not found. A majority of all possible (pair-wise) interdependencies were observed. Correlations between 50% of the pairs of infrastructures were statistically significant. No significant relationship was found between type of infrastructure and type of interdependency.

Most infrastructures experienced more noninterdependency-related disruptions than interdependency-related ones. The exceptions were the civil infrastructures of telecom, power, oil and gas, and water. Infrastructures such as government services and banking that depend on civil infrastructures in order to provide their services had a lower proportion of interdependency-related disruptions. Emergency services, which often depend upon transpor-

tation, had an almost equal number of interdependency- and noninterdependency-related disruptions. It may be that infrastructures such as government services and banking have an impact that is broader than that of civil infrastructures, impacting the national or international economy and population, rather than other critical infrastructures.

Summary

The 2001 World Trade Center attack led to many incidents that disrupted critical infrastructures and the services they provide. This study illustrates some of the consequences of these incidents, particularly in relation to interdependencies among critical infrastructures. As shown in Table 16, the 196 reported incidents resulted in 238 disruptions to eight critical infrastructures. Among the disruptions, 169 did not involve interdependencies, 46 did.

The data were explored by answering three questions, the answers to which are now summarized.

1. *What incidents were reported that led to disruptions in critical infrastructures?* The number of incidents reported in Week 1 was large relative to subsequent weeks. Incidents persisted throughout the study period but diminished overall.
2. *What disruptions to the services provided by critical infrastructures resulted from these incidents?* In Week 1, most reported disruptions impacted transportation, government services, and banking, while oil and gas and water saw very few disruptions. In Weeks 2–13, the number of disruptions per week generally decreased, though with some fluctuation. The number of disruptions to banking was significantly higher than the number to emergency services, water, power, and oil and gas. It may therefore be said that the attack had differential impacts across infrastructures over time.
3. *What interdependencies among disrupted critical infrastruc-*

Table 9. Interdependencies: Week 1

Date	Input	Shared	Colocation	Exclusive-or (XOR)	None	Total
September 12	4	0	2	0	22	28
September 13	0	0	6	0	23	29
September 14	0	0	1	1	10	12
September 15	1	0	2	0	9	12
September 16	3	0	5	1	4	13
Total	8	0	16	2	68	94

Table 10. Interdependencies: Weeks 2–13

Week	Input	Shared	Colocation	Exclusive-or (XOR)	None	Total
2	4	0	3	0	21	28
3	3	0	2	0	19	24
4	1	0	0	0	14	15
5	0	0	3	0	15	18
6	0	0	0	0	1	1
7	0	0	0	0	4	4
8	1	0	2	0	10	13
9	0	0	1	0	2	3
10	0	0	0	0	5	5
11	0	0	0	0	5	5
12	0	0	0	0	4	4
13	0	0	0	0	1	1
Total	9	0	11	0	101	121

Table 11. Number of Disruptions: Weeks 1–13

Week(s)	Interdependency				Total
	Input	Colocation	Exclusive-or (XOR)	None	
1	8	16	2	68	94
2–13	9	11	0	101	121
1–13	17	27	2	169	215

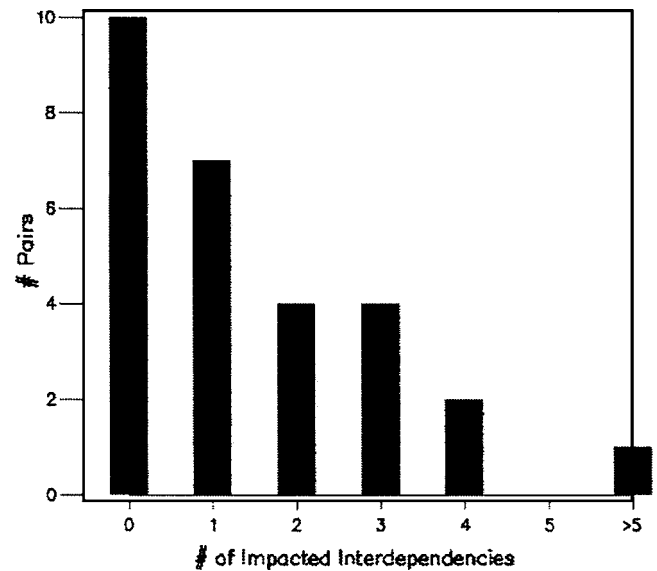
tures were impacted? Approximately 20% of reported disruptions involved interdependency. Input, colocation, and XOR interdependencies were found, with colocation occurring most frequently. Shared interdependency was not found. A majority of all possible (pairwise) interdependencies were observed, the majority of which were significant. No significant relationship was found between type of infrastructure and type of interdependency.

Discussion and Recommendations

This research has shown how various disruptive incidents impacted critical infrastructures in New York City in the months following the 2001 World Trade Center attack, with a particular focus on impacts involving infrastructure interdependence. On a day-to-day basis, these infrastructures are managed by a variety of organizations (e.g., government agencies, private firms, and not-for-profit authorities) with varying degrees of independence from each other but overlapping information needs. One important goal of these organizations following a disaster is to continue to provide services as effectively and safely as possible. Infrastructure interdependencies that become salient during response and recovery must therefore be managed in order to respond effectively and restore services. As a result, crisis managers must have access to information that enables them to understand interdependencies and their actual or potential impacts. Without a requirement for managers of different infrastructures to collaborate and coordinate during routine operations, it may be necessary to establish such an outside agency to do so during disaster response and recovery. Emergency operations centers established by state and local governments in response to a disaster are candidates for this responsibility since part of their function is to facilitate inter-organizational decision making (Mendonça and Wallace 2004; Scanlon 1994). These efforts may be further supported by the development of emergency response plans and training exercises that take into account the need to coordinate response and restoration activities and information among multiple organizations.

Table 12. Disruptions to Critical Infrastructure Services: Weeks 1–13

	Emergency services	Transportation	Telecommunications	Government services	Power	Oil and gas	Banking	Water
Emergency services	—	2	2	3	4	0	1	0
Transportation	2	—	0	1	3	1	2	3
Telecommunications	2	0	—	1	3	1	11	4
Government services	3	1	1	—	0	0	2	0
Power	4	3	3	0	—	0	1	0
Oil and gas	0	1	1	0	0	—	0	1
Banking	1	2	11	2	1	0	—	0
Water	0	3	4	0	0	1	0	—

**Fig. 4.** Frequency of disruptions by pairs of infrastructures

More extensive and uniform reporting of incidents could improve organizations' capabilities for after-action reporting, particularly when that reporting is focused on assessing the impacts of infrastructure interdependence. A key challenge is achieving extensive reporting across the various infrastructure systems, since from this analysis it may be surmised that interdependency is likely to be found among many combinations of infrastructures. As a public data source of recognized quality, the *New York Times* can be expected to report on events of general interest, though it is of course possible that while certain incidents (e.g., those likely to be of greatest interest to the general public) were well represented, others might not have been. A uniform reporting system could support rapid analysis of the data, reducing the need for content coding of incident reports. It would also help ensure that the various definitions of infrastructure and interdependence are used consistently across the reporting organizations. Indeed, some of the definitions used for this study continue to be revised and augmented. Uniform reporting might also result in measures of the severity of disruptions, which would support a more detailed analysis of the degree of interdependency between various infrastructures. As an example, severity could be measured on an ordered scale, ranging from none (no impact) to high (complete loss of service). An assessment of severity might also include information about the direction of the disruption (as in the case of an input interdependency from power to banking) as well as the

Table 13. Illustrative Data for Correlation Calculation

Index	Emergency services	Transportation
1	1	0
2	1	0
3	1	1
4	1	0
5	0	1
6	0	1

geographic region involved (e.g., city block versus individual building). When coupled with the methodology described here, a more extensive and uniform reporting system could therefore more readily support planning and decision making activities in the management of critical infrastructures.

There will also be a need to address those risks related to infrastructure systems that emerge during response and restoration activities. Different interdependencies may require different risk management strategies. The presence of an exclusive-or interdependency may lead to negotiations among possibly competing organizations over which of two or more infrastructures may utilize the interdependent component. As another example, the presence of an input interdependency from one infrastructure to one or more others may lead to discussions about which levels of service to provide to the various input-dependent infrastructures. In the days immediately following the World Trade Center attack, restoration of financial services in New York City was put at a high priority as part of the effort to reopen the New York Stock

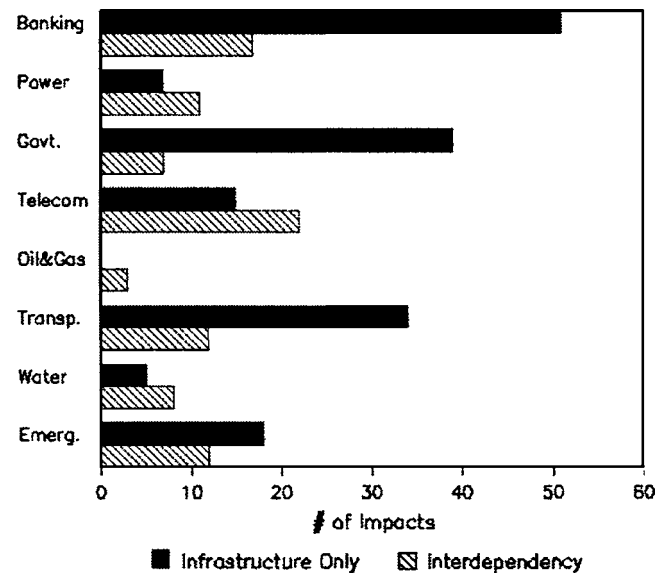


Fig. 5. Disruptions to services: Weeks 1-13

Exchange. The restoration of services required first the provision of power and then of communications, at the expense of other business and home services.

Finally, interdependencies that become salient during response and recovery might not be “planned for.” An example is the interdependency shown in Fig. 1, which occurred between transpor-

Table 14. Disruptions of Critical Infrastructure Services: Weeks 1-13

	Emergency services	Transportation	Telecommunications	Government services	Power	Oil and gas	Banking	Water
Emergency services	1.0000	0.1023	-0.0782	-0.0983	0.0572	-0.0397	-0.2468	-0.1042
	—	0.1538	0.2757	0.1705	0.4262	0.5806	0.0005	0.1460
Transportation	0.1023	1.0000	-0.1898	-0.2261	-0.0169	0.1887	-0.3316	0.1023
	0.1538	—	0.0077	0.0014	0.8142	0.0081	<0.0001	0.1537
Telecommunication	-0.0782	-0.1898	1.0000	-0.1862	0.1503	0.1007	-0.0841	0.1199
	0.2757	0.0077	—	0.0090	0.0355	0.1603	0.2413	0.0941
Government services	-0.0983	-0.2261	-0.1862	1.0000	-0.1526	-0.0538	-0.3256	-0.1413
	0.1705	0.0014	0.0090	—	0.0327	0.4537	<0.0001	0.0482
Power	0.0572	-0.0169	0.1503	-0.1526	1.0000	0.1617	-0.1645	0.0004
	0.4262	0.8142	0.0355	0.0327	—	0.0235	0.0212	0.9956
Oil and gas	-0.0397	0.1887	0.1007	-0.0538	0.1617	1.0000	-0.0724	0.1769
	0.5806	0.0081	0.1603	0.4537	0.0235	—	0.3136	0.0131
Banking	-0.2468	-0.3316	-0.0841	-0.3256	-0.1645	-0.0724	1.0000	-0.1899
	0.0005	<0.0001	0.2413	<0.0001	0.0212	0.3136	—	0.0077
Water	-0.1042	0.1023	0.1199	-0.1413	0.0004	0.1769	-0.1899	1.0000
	0.1460	0.1537	0.0941	0.0482	0.9956	0.0131	0.0077	—

Table 15. Summary of Disruptions by Interdependency and Infrastructure: Weeks 1-13

Interdependency	Emergency services	Transportation	Telecommunications	Government services	Power	Oil and gas	Banking	Water	Total
Input	4	6	10	3	3	0	8	0	34
Colocation	6	6	12	4	7	3	8	8	54
Exclusive-or (XOR)	2	0	0	0	1	0	1	0	4
Subtotal	12	12	22	7	11	3	17	8	92
None	18	34	15	39	7	0	51	5	169
Total	30	46	37	46	18	3	68	13	261

Table 16. Summary of Incidents and Disruptions

Week	Incidents	Disruptions	Interdependency	Noninterdependency
1	81	104	26	68
2	26	32	7	21
3	23	26	5	19
4	15	16	1	14
5	15	20	3	15
6	1	1	0	1
7	4	4	0	4
8	13	16	3	10
9	3	4	1	2
10	5	5	0	5
11	5	5	0	5
12	4	4	0	4
13	1	1	0	1
Total	196	238	46	169

tation and emergency services infrastructures and prevented either infrastructure from functioning at prescribed levels. There are other examples of such emergent interdependencies following the attack (Mendonça 2006), and similar observations may be made about the human systems within the organizations that managed these infrastructures. Approaches to planning for and responding to impacts on critical infrastructures may therefore benefit from activities which improve managers' capabilities for responding to the unexpected (Kreps 1991).

In conclusion, this analysis has provided an assessment of the nature and extent of disruptions to critical infrastructures in the months following the 2001 World Trade Center attack, and has provided some empirical evidence for viewing critical infrastructures as "systems of systems" (Peerenboom et al. 2001; Wallace et al. 2003)—a viewpoint that may help improve society's capability to maintain quality of life, both in normal times and in extraordinary situations.

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