IDENTIFICATION AND CLASSIFICATION OF RESTORATION INTERDEPENDENCIES IN THE WAKE OF HURRICANE SANDY

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ABSTRACT

This paper introduces the new concept of *restoration interdependencies* that exist among infrastructures during their restoration efforts after an extreme event. Restoration interdependencies occur whenever a restoration task in one infrastructure is impacted by a restoration task, or lack thereof, in another infrastructure. This work identifies examples of observed restoration interdependencies during the restoration efforts after Hurricane Sandy as reported by major newspapers in the affected areas. A classification scheme for the observed restoration interdependencies is provided which includes five distinct classes: traditional precedence, effectiveness precedence, options precedence, time-sensitive options, and competition for resources. This work provides an overview of these different classes by providing the frequency

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they were observed, the infrastructures involved with the restoration interdependency, and discussing their potential impact on interdependent infrastructure restoration.

Keywords: Restoration Interdependencies, Hurricane Sandy, Scheduling

INTRODUCTION

The purpose of this work is to explore the new concept of *restoration interdependencies* that exist among infrastructures during their restoration efforts after an extreme event. Our particular focus is on this concept around Hurricane Sandy, which affected areas in and around New Jersey, New York City, and Long Island in late October 2012. The storm had significant effects on infrastructures in these areas; the United States Department of Energy Delivery and Reliability (2012) reports that at its peak, 2,097,933 customers were without power in New York, 2,615,291 customers were without power in New Jersey, 57 terminals associated with fuel distribution were closed, and refineries in the area lost around 40% of their operating capacity. Therefore, restoration of services provided by these infrastructures required a significant effort. Restoration interdependencies occur whenever a restoration task, process, or activity in one infrastructure is impacted by the restoration (or lack thereof) of another infrastructure. This includes situations when a restoration task in infrastructure B requires the disrupted *services* provided by infrastructure A to be completed and, therefore, the lack of restoration of these disrupted services in A would prevent the task in B from being started. As an example, debris or flooding that blocks access into an area and prevents work crews from accessing damaged components of the power infrastructure is a restoration interdependency: the restoration of the damaged power components is delayed due to the unavailability of roads (or, equivalently, lack of restoration) in the road network. This work: (i) identifies examples of such restoration interdependencies as reported through major newspapers in the areas affected by Hurricane Sandy, (ii) provides a classification scheme for restoration interdependencies, and (iii) discusses the potential impact of them on post-event decision-making in infrastructure restoration.

Restoration efforts, by their nature, involve scheduling resources to activities that restore or repair damaged components in an infrastructure, install new (temporary) components within an infrastructure, or produce some level of functionality within the infrastructure. The term 'resource' is broadly defined in the sense they could model work crews, machines (e.g., pumps or generators), or individual personnel. Much like how the operations of infrastructures depend on other infrastructures, the restoration efforts of an infrastructure are impacted by the restoration efforts of other infrastructures. The focus of this paper is to identify, classify, and discuss the role of these restoration interdependencies which are defined as:

> **Definition**: A *restoration interdependency* occurs when a restoration task, process, or activity in an infrastructure is impacted by a restoration task, process, or activity (or lack thereof) in a different infrastructure.

This definition is based on the broad interpretation that restoration efforts involve any task, process, or activity that is done in order to restore an infrastructure back to normal operating conditions (or an equivalent state). The distinguishing characteristic for an incident to be classified as a restoration interdependency is that *the restoration efforts* of the initial infrastructure are impacted by the timing of restoration tasks (e.g., restoring disrupted services) in the other infrastructure. This characteristic distinguishes restoration interdependencies from *operational interdependencies* (for an overview, see the recent survey paper of Ouyang (2014)) where a component of one infrastructure requires services provided by another infrastructure to properly function and *infrastructure failure interdependencies* (see Chang et al. (2005), McDaniels et al. (2007), and McDaniels et al. (2009)) where a failure in an initial infrastructure cascades to cause failures in other infrastructures. In addition, restoration interdependencies will only occur when an extreme event causes damage to multiple infrastructures thereby necessitating restoration efforts in each of the damaged infrastructures. Operational interdependencies exist in the day-to-day operations of the infrastructures and infrastructure failure interdependencies can occur with damage to only a single infrastructure.

Restoration interdependencies can, to a certain extent, link the restoration efforts of infrastructures. Therefore, the schedule of restoration efforts of an infrastructure may be impacted by its restoration interdependencies. Certain restoration interdependencies are closely tied to concepts such as precedence constraints from the field of scheduling (see Pinedo 2012 for an overview) with one important distinction: in a traditional scheduling problem, all available scheduling resources are controlled by a central decision-maker. However, in the case of infrastructure restoration, the scheduling resources are often controlled by different infrastructures, private sector companies, public sector agencies, and the government. This means an understanding of restoration interdependencies may help to better understand the level of communication and/or coordination required across infrastructures when responding to an extreme event.

An individual infrastructure can plan their restoration efforts based on the damage to their infrastructure caused by the extreme event. This plan helps to predict when restoration tasks will be complete and change the set of operational components within the infrastructure thus restoring disrupted services. However, restoration interdependencies can impact this prediction by delaying the start time (or effectiveness) of planned restoration tasks since restoration tasks in other infrastructures can impact the planned efforts. The concept of information-sharing, where certain key agencies and infrastructures share their planned restoration efforts, can help to mitigate the impact of restoration interdependencies on the effectiveness of the restoration efforts. This is because infrastructures can better plan for the impact of restoration interdependencies on their planned efforts. Therefore, the introduction and analysis of restoration interdependencies is important since it provides a new understanding of how the restoration efforts of infrastructures are linked across systems and motivates the need for potential information-sharing in interdependent infrastructure restoration.

COMPARISON OF RESTORATION, OPERATIONAL, AND FAILURE

INTERDEPENDENCIES

It is important to discuss and differentiate *restoration interdependencies* from the well-studied concepts of *operational interdependencies* and *infrastructure failure interdependencies* (IFIs). There are certain situations in which restoration tasks in a particular infrastructure affect when *services* provided by another infrastructure are restored but do not necessarily impact the restoration efforts of this other infrastructure. This would imply an operational interdependency, not a restoration interdependency. The focus of this section is to discuss relevant literature on these other interdependencies and then present some examples, in the context of Hurricane Sandy, to illustrate these differences between them and restoration interdependencies.

This paper broadly defines an *infrastructure* to be any system that provides services or delivers goods to the citizens of a society. This includes traditional civil infrastructures (such as power, natural gas, water, telecommunications, and transportation systems) that maintain and operate their own system components as well as 'social infrastructures' (such as emergency medical services, a fuel supply chain, or a food supply chain) whose system relies on their own components (e.g., terminals and gas stations for a fuel supply chain) as well as civil infrastructure (e.g., the road system). This definition is in line with presidential initiatives (The White House, Office of the President 2013) that define critical infrastructure sectors (currently there are 16 such sectors) including ones with both civil (e.g., Transportation) and social (e.g., Healthcare) components. It is important to note that our work will first focus on *specific infrastructures* within each sector rather than the sector as a whole (e.g., the power infrastructure instead of 'Energy') in order to present detailed infrastructure-by-infrastructure analysis. We then present an 'aggregate' analysis of the restoration interdependencies observed across a sector in order to examine the differences between the 16 critical infrastructure sectors.

The concept of *operational interdependencies* between critical infrastructures has been well-studied. Rinaldi et al. (2001), Little (2002), and Wallace et al. (2003) provide definitions and discussions of this concept. Operational interdependencies occur when a component of one infrastructure requires services provided by another infrastructure in order to properly function. These types of interdependencies can cause cascading failures (see, for example, McDaniels et al. 2007, Lee et al. 2007, and Chou and Tseng 2010) where the disruption of services in one infrastructure causes disruptions and failures in other infrastructures that rely on its services. Mendonca and Wallace (2006) provide an overview of the operational interdependences observed after the terrorist attacks of September 11, 2001 on New York City's critical infrastructure systems. Our work presents a similar overview of restoration interdependencies observed after Hurricane Sandy.

The concept of *infrastructure failure interdependencies* (IFIs) has also been studied by Chang et al. (2005), McDaniels et al. (2007), and McDaniels et al. (2009). McDaniels et al. (2007) define IFIs as "failures in interdependent infrastructure systems that are due to an initial infrastructure failure stemming from an extreme event." These works examined a framework for IFIs by specifically focusing on them arising after large-scale disruptions to the power infrastructure, since this system is a critical lifeline for society (see, e.g., Reed et al. 2006). IFIs and restoration interdependencies are related in the sense that they arise after an extreme event impacts (a subset of) interdependent infrastructure systems. Restoration interdependencies are distinct from IFIs since they focus on the restoration efforts of infrastructures as opposed to the how an initial failure causes cascading disruptions of services to other infrastructures.

We now present an example to illustrate the differences between these different types of interdependencies. The subway system needs power to its components in order for trains to run their scheduled routes. Therefore, damage to a substation in the power system that provides power to a subset of subway components would cause a disruption of subway services. This means that subway services would not be restored until power restoration work crews repair the damaged substation and thus restore power to subway components. This situation represents an operational interdependency: the operations of the subway system are dependent on the services provided by the power system. Further, the *disruption* of services provided by the subway system constitutes an infrastructure failure interdependency since the initial failure in the power infrastructure caused a failure in the subway system. This situation is not a restoration interdependency because there were no restoration tasks in the subway system that were dependent on power and thus impacted by power restoration efforts.

However, there were restoration tasks in the subway system after Hurricane Sandy that were dependent on disrupted power. For example, Flegenheimer (2012) discusses that test trains needed to be run in the subway system prior to running scheduled routes in order to test the repairs done in the subway system. The running of test trains would be a restoration task in the subway system since it was an activity that needed to be done to restore the subway back to normal operating conditions after Hurricane Sandy. Therefore, this would constitute a restoration interdependency between the subway system and the power system: test trains could not be run (the restoration task in the subway system) until power was restored to the subway system (a restoration task in the power infrastructure).

Another example with the subway and power system was that the water in the subway needed to be pumped out before damage could be assessed and repaired in the subway system. This restoration task could not begin until either power was restored to an area (a restoration task in the power infrastructure) or until a generator and fuel were brought to the subway (a restoration task in the subway infrastructure). This represents a different type of restoration interdependency than the previous example since there are options for which infrastructure needs to complete a task before the pumping task can begin.

There is a certain type of 'quasi-operational interdependency' that exists when a restoration task in an infrastructure relies on the services provided by another infrastructure and the required services *have not been disrupted*. For example, the running of test trains on a subway line requires power and if power was not disrupted then this restoration task could be conducted as planned. The fact that power was not disrupted and, therefore, does not need to be restored means that this situation does not constitute a restoration interdependency since the restoration efforts of power do not impact the restoration efforts of the subway system. Note, though, that if power was disrupted to the subway line, then we have a restoration interdependency since the time of power restoration to the line impacts when the test trains can be run. The focus of this paper is on situations when the restoration efforts of infrastructures are linked in terms of temporal, precedence, and resource considerations. Therefore, these 'quasi-operational' interdependencies do not fall within this focus.

LITERATURE ON MODELING INFRASTRUCTURE RESTORATION

Mathematical models have been developed to measure the reliability or the vulnerability of interdependent systems, including predicting cascading failures based on damage to the systems, see, for example, Dueñas-Osorio et al. (2007), Barker and Haimes (2009a), Barker and Haimes (2009b), Matisziw et al. (2009), Winkler et al. (2011), and Ouyang and Dueñas-Osorio (2011). A common modeling approach is to view infrastructures as *networks* and examine their topological features or view the *services* provided by them as flow in the network (for an overview of network flows, see Ahuja et al. 1993). Lee et al. (2007) and Lee et al. (2009) provide network modeling approaches to capture different classes of operational interdependencies that may exist between infrastructures. The models of Lee et al. (2007) and Lee et al. (2009) can be used to measure the level of disruptions throughout a set of interdependent infrastructures resulting from damage. In general, network models of the operations of infrastructures allow one to capture the services provided by the systems given a set of operational components and can help to capture operational and infrastructure failure interdependencies.

There has also been work examining mathematical models to determine the restoration (or recovery) efforts of an infrastructure in response to damage that was caused by an extreme event. Guha et al. (1999), Ang (2006), Xu et al. (2007), Coffrin et al. (2011), and Nurre et al. (2012) present models for the restoration of a power infrastructure. Cagnan and Davidson (2003) present a simulation-based approach for restoring power and water systems. Matisziw et al. (2010) present a model for restoring infrastructures, such as telecommunications, where connectivity between components is important. Yan and Shih (2009) and Stilp et al. (2012) focus on debris clearance operations in the transportation (road) infrastructure. Shoji and Toyota (2009) examine graph theory-based qualitative methods to understand the restoration process of interdependent infrastructure systems. Cavdaroglu et al. (2013) present a model for the restoration efforts in a single infrastructure that considers its operational interdependencies with other infrastructures. An important aspect of many of these models is to recognize that scarce resources (such as work crews) need to be allocated to restoration activities, tasks, or processes over time. Therefore, these models focus on *scheduling* the restoration efforts of the infrastructure. The network models of infrastructures then play an important role in these scheduling models since they allow for an assessment of the operations of an infrastructure based on the set of operational components (which include repairs done to the infrastructure) at any point in time. A natural step in examining restoration interdependencies will be to model them within a scheduling framework for interdependent infrastructure restoration.

METHODS FOR IDENTIFICATION OF RESTORATION INTERDEPENDENCIES

The purpose of this section is to describe the methods used to identify restoration interdependencies. The intent of our analysis is to document observed examples of restoration interdependencies and provide a classification scheme. The focus of the identification process to determine examples was on the online versions of major newspapers in the areas affected by Hurricane Sandy. This focus was selected to ensure that the news articles were reputable and had proper protocols in place when collecting information to publish the articles. It is further important to note that our focus is on observations associated with the existence of a restoration interdependency as opposed to data surrounding it (for example, how long it took before the restoration interdependency was known to all infrastructures involved). Therefore, errors in reporting the data associated with the incident are very unlikely to impact this work.

The newspapers that were selected and the areas that they represent include The New York Times (New York City), Newsday (Long Island), The Star Ledger (New Jersey), and The Philadelphia Inquirer (South New Jersey and Philadelphia). The online versions of some of these newspapers are essentially a collaboration between themselves and local newspapers, so our investigation went beyond these 4 newspapers. We specifically focused our search on articles that appeared in these newspapers (or their online presence) within three months of Hurricane Sandy's landfall - from October 29, 2012 to January 31, 2013.

These newspapers had either an entire section devoted to Hurricane Sandy or an article tag of Hurricane Sandy that could be utilized to identify all articles posted relevant to Hurricane Sandy. These sections (or the tag search) would bring up a list of articles related to Hurricane Sandy and the titles of these articles helped determine whether they could potentially discuss restoration interdependencies. Based on the titles, an initial cut was made to articles that clearly did not discuss restoration activities. For example, articles that focused on benefit concerts or dinners would be cut and not read. If the title was deemed to potentially discuss restoration activities after Hurricane Sandy, it was then reviewed and, if applicable, quotations were identified that discussed potential restoration interdependencies. If quotations were identified, the articles were saved and recorded into a database.

We now discuss specific details about each of the newspapers used for this work. In particular, we discuss how we identified all Hurricane Sandy related articles and also the relationships between the online version of the newspapers and other local papers. These details are:

- **The New York Times**: The online version can be accessed at www.nytimes.com. There is specific section under "Times Topics" for "Hurricanes and Tropical Storms" that listed all articles with a tag of Hurricane Sandy.
- **Newsday**: The online version can be accessed at www.newsday.com. There is a section dedicated to Hurricane Sandy at www.newsday.com/long-island/sandy. The articles within this section are grouped by specific areas, such as "Long Island Recov-

ers" and "Latest on LIPA" (LIPA is Long Island Power Authority), which helped in identifying appropriate articles discussing restoration efforts.

- **Star Ledger**: The online version can be accessed at www.nj.com. There is a specific section on the site dedicated to Sandy at www.nj.com/hurricanesandy/. After clicking on 'Load More' a few times, an option appears that allowed for an exploration of articles relevant to Hurricane Sandy by publication month. This site is a collaboration between the Star Ledger and local newspapers throughout New Jersey, hence reporters from all associated newspapers post articles to the site. There were many relevant articles from local newspapers, so we included an 'Other NJ Papers' source in our classification.
- **Philadelphia Inquirer**: The online version can be accessed at www.philly.com. This site is a collaboration with the Philadelphia Daily News, hence reporters from both newspapers post articles to the site. A search was conducted with the keyword "Hurricane Sandy" to access relevant articles on the site.

Through this process, a database of 331 potentially relevant quotations were collected from 175 articles. A coding scheme was developed to then classify different types of restoration interdependencies. Note that not all quotations ended up concerning a restoration interdependency, so they were omitted from the observations. This was often due to the quotation discussing an operational interdependency (e.g., a subway line was not running due to lack of power) as opposed to a restoration interdependency. Note that multiple quotations may be associated with the same incident reported on by different sources. Using the coding scheme, a person classified all quotations into different classes of restoration interdependencies (including a 'not relevant' classification) resulting in a total of 84 quotations dealing with observed restoration interdependencies. Another person went through a random sampling of 10% of the quotations in order to test the consistency of the coding scheme. This person's classification matched (100% agreement) that of the original classification, validating the consistency of the coding scheme.

CLASSIFICATION OF RESTORATION INTERDEPENDENCIES

The focus of this section is on presenting the classes of restoration interdependencies identified from the various newspaper articles. The different classes of restoration interdependencies fall into one of two broad categories: time-based interdependencies (which are the traditional precedence, effectiveness precedence, options precedence, and time-sensitive options classes) and resource-based interdependencies (which is the competition for resources class). The time-based interdependencies typically concern the timing of restoration tasks across infrastructures while the resource-based interdependencies concern how restoration resources are distributed across infrastructures. For each specific restoration interdependency class, its definition will be provided and a few illustrative examples, from Hurricane Sandy, will be discussed. In addition, Table 1 provides an overview of which restoration interdependencies were observed between different types of infrastructures. The entry in the table (Infrastructure A, Infrastructure B) provides all classes of restoration interdependencies between these two infrastructures as described below.

Traditional Precedence

Definition: A restoration task in infrastructure B cannot be started until a restoration task in infrastructure A is complete.

Observed Frequency: 46.

Examples (A, B):

- (Power, Subway). The running of a test train in the subway system cannot start until power has been restored to the path of the test train (Flegenheimer 2012).
- (Port System, Fuel Supply Chain). The distribution of gas to restore normal levels of reserves at gas stations cannot start until debris is cleared from harbors and ports (Lipton and Krauss 2012, Hu 2012).
- (Power, Commercial Supply Chain). Assessment activities to determine damage to production equipment at a facility cannot begin until power is restored to that facility

(Associated Press 2012).

- (Residential, Power). Power can not be turned back on to a residence or commercial business until their electrical systems are assessed (Issler and Brodsky 2012).

Discussion: There were two main causes that led to the traditional precedence restoration interdependency: (i) the restoration task in infrastructure B required the restoration of disrupted services in infrastructure A and (ii) the restoration task in infrastructure A prevents the start of the restoration task in infrastructure B. Examples of the former include when power needs to be restored to test equipment in a commercial supply chain or the road system needs to allow for access to assess damaged components within the natural gas infrastructure. Examples of the latter include when the closing of a port prevents tankers carrying fuel (which will be used to restore reserves to normal levels) from delivering it through the port and when power work crews must clear and/or fix downed wires before downed trees can be cleared from a road.

The power infrastructure was involved as both infrastructure A and infrastructure B in many observed traditional precedence restoration interdependencies. There were situations where *components* in the power infrastructure needed to be safely moved or repaired prior to restoration tasks being started in other infrastructures (e.g., the repair of telecommunications lines needed power poles to be repaired). There were also situations when restoration tasks in other infrastructures needed the restoration of power to be completed. An interesting situation that arose with the power infrastructure after Hurricane Sandy was that residential neighborhoods which were flooded during the event would not have their power restored until the electrical systems of the impacted houses were either inspected or switched off the grid.

Effectiveness Precedence

Definition: A restoration task in infrastructure B is not as effective (for example, it requires a longer processing time or more resources dedicated to it) until a restoration task in infrastructure A is complete.

Observed Frequency: 5.

Examples (A, B):

- (Power, Subway). Pumping floodwaters from subway lines or tunnels is slowed by electrical shortages; thereby implying that restoring power to the appropriate area would speed up the pumping efforts (Flegenheimer and Leland 2012).
- (Power, Road System). The restoration of power to a pumping station would help drain floodwaters from a road (Ma 2012).

Discussion: The term 'effectiveness' is meant to be broad and improving effectiveness of the restoration task in infrastructure B after the completion of the task in infrastructure A can take a variety of forms. For example, in the provided examples, mobile pumps could be brought to the subway line or the road to remove the floodwaters (the restoration task) and the pumping process would take shorter if electricity was restored to the permanent pumps in the area. We observed situations where the processing time of a restoration task would decrease and situations where a restoration task would be made simpler by completing the restoration task in infrastructure A.

Options Precedence

Definition: A restoration task in infrastructure B can be completed by accomplishing a restoration task in one of a set of possible infrastructures, A_1, A_2, ..., A_n.

Observed Frequency: 15.

Examples (A_1, A_2, B):

- (*Power, Fuel Supply Chain*, Fuel Supply Chain). A gas station could begin its re-opening process by either having its power restored or receiving a generator (Goldberg 2012).
- (*Power, Hospital*, Hospital). Bellevue Hospital lost both power and its backup generators, but still needed to provide comfort and safety for its patients; the restoration

of this service could be provided by either power restoration to the hospital or the evacuation of the patients from the hospital (Hartocollis and Bernstein 2012).

Discussion: Many of the observed options restoration interdependencies typically involve how infrastructure B can deal with the disruption in services of another infrastructure and infrastructure B will often appear as one of the 'A' infrastructures. For example, a gas station in the fuel supply chain could either be supplied an emergency generator (a task in the fuel supply chain) or have its electrical power restored (a task in the power infrastructure) for the gas station to begin its reopening process (a task in the fuel supply chain). As another example, a hospital (or senior care facility) may need to restore its normal operations (i.e., providing comfort and safety to its patients) should its back-up generators fail and power is disrupted to it. This could be done by either evacuating their patients (a task in the hospital infrastructure) or power being restored (a task in the power infrastructure). It is likely that the frequency of this class is much higher than observed since whenever a restoration task in an infrastructure requires power and power is disrupted, the infrastructure has the option to either bring in a generator or wait for power to be restored. Further, as will be discussed in the analysis section, the timing of an observed incident of this restoration interdependency is often a function of the criticality of the restoration task in infrastructure B.

Time-Sensitive Options

Definition: A restoration task in infrastructure B must be completed only if a restoration task in infrastructure A is not completed by a certain (unknown) deadline. Therefore, the restoration task in A must be completed by its deadline or the task in B must be completed.

Observed Frequency: 11.

Examples (A, B):

- (Power, Wireless Telecommunications). Power is not restored before a generator, which powers a cell tower, runs out of fuel which creates a restoration task of refueling the generator within the telecommunications infrastructure (Stein 2012).

- (Road System, Residential). Firefighters cannot access a fire (thus providing emergency services) because flooding prevents access to the location of the fire, which allows the fire to spread and creates more residential cleanup tasks (Heyboer 2012).

Discussion: The most frequently reported situation for this restoration interdependency involved a situation where the deadline for the task in infrastructure A is unknown: a road system has not been restored by the time a fire starts (this time is unknown) and, therefore, the fire spreads to more residential areas. However, a situation that is probably more common, but less frequently reported, is one where if power is not restored by a certain time, the emergency generators of an infrastructure need to be refueled. This was observed for wireless telecommunications but could occur whenever an infrastructure system has its own backup generators (e.g., water or waste water treatment plants).

Competition for Resources

Definition: Restoration tasks in infrastructures A_1, A_2, ..., A_n compete for the same set of scarce resources.

Observed Frequency: 9.

Examples ($\mathbf{A_1}$, $\mathbf{A_2}$, ..., $\mathbf{A_n}$):

- (Emergency Shelters, Public (Education) Services). Emergency shelters and educational services compete for location-based resources, such as both being located at a school (Bernstein 2012).
- (Hospital, Water, Waste Water). The location of power generators brought into an area could assist with restoring electricity to hospitals, the water system, or waste water treatment plants (Johnson 2012).

Discussion: It was common to observe that the infrastructures were competing for either generators or fuel. It could be argued that most infrastructures are competing with each other for the 'fuel resource,' especially given the shortages observed after Hurricane Sandy, since fuel is critical in moving personnel and other restoration resources to their desired locations. It is also possible that *personnel* are the resources for which the infrastructures are competing; for example, skilled arborists could be used by both the power infrastructure and the road system when clearing trees for their restoration activities.

ANALYSIS OF OBSERVED RESTORATION INTERDEPENDENCIES

The focus of this section is on providing analysis of the restoration interdependencies that were observed after Hurricane Sandy. It is important to recognize that our database of observed incidents does not necessarily include all actual instances of restoration interdependencies or even a random sample of instances since we focused on instances that were reported by newspapers. However, preliminary analysis on the observed incidents can help to explore conjectures about the relationships and timing involved with restoration interdependencies. In terms of this analysis, we first provide the frequency of such restoration interdependencies (as observed by the number of quotations found in articles discussing them). We then provide a temporal analysis associated with the observed restoration interdependencies. Finally, we present the types of restoration interdependencies that were observed between the infrastructures within the different critical infrastructure sectors defined by the U.S. Department of Homeland Security.

Frequency Summary

Table 2 provides the frequency of each of these different classes of restoration interdependencies based on the news articles found from each source. Overall, we observed 84 instances that fit our coding scheme in defining and identifying restoration interdependencies. The traditional precedence restoration interdependency is by far the one that was most commonly observed (45 instances); the options precedence restoration interdependency (15 instances) was the next most frequently observed.

Temporal Analysis

This section focuses on the temporal analysis of the observed restoration interdependencies. Although the set of observed incidents may not include all actual instances, we feel the data supports certain conjectures concerning the timing of these restoration interdependencies. Figure 1 provides a timeline of the reported date of the observed restoration interdependencies, broken down by type, during the first two weeks after Hurricane Sandy. Hurricane Sandy made landfall in the areas where this study was focused on October 29, 2012 and 73 of 84 (86.9%) observed restoration interdependencies were reported during these first two weeks. It should be noted that many of the other 11 incidents not covered in this figure were from articles that are more overviews of the impacts of Hurricane Sandy and, therefore, do not necessarily report on incidents that have occurred well past the date of Sandy. The largest number of observations on a single day was 17 which were reported two days after the storm (on October 31, 2012) and the following day (November 1, 2012) 13 observations were identified. Figure 1 demonstrates that there is a surge in the number of restoration interdependencies during the first few days after Hurricane Sandy and then the number becomes less significant a week past it.

One key point in the identification process is that a restoration interdependency will, typically, not be reported until an infrastructure (or infrastructures) encounter the restoration interdependency. Therefore, we can obtain insights by examining the distribution of *when* certain classes of restoration interdependencies were observed. Figure 2 provides an analysis, for each class of restoration interdependencies, of the percentage of the total observations of that class that were obtained by a certain date. For example, roughly 9% of time-sensitive options observations were reported within 1 day of Hurricane Sandy, 63% were reported within 2 days, and 90% were reported within 8 days. This property can be attributed to the fact that many of the time-sensitive options observations encountered dealt with roadways blocking access to fires, which allowed them to spread and create more clean-up activities. Therefore, as roadways were cleared after the event, this type of incident became less frequent. The competition for resources interdependency also exhibits a rapid increase in these percentages within the first 7 days after the event, which can be attributed to the fact that as services are restored the resources that were necessary (e.g., fuel and generators) become more abundant.

The traditional, effectiveness, and options classes exhibit a more steady (e.g., closer to linear) trend in the growth of their percentage of observations as a function of time. This linear relationship is conjectured to have more to do with the time of *observation* of the interdependency than the time of *occurrence* of the interdependency. For example, the reported incidents of the traditional precedence class imply that infrastructure B had resources to attempt the restoration task but it was prevented from starting due to its restoration interdependency. Therefore, with limited resources available for infrastructure restoration, it may be some time before a resource in infrastructure B could be allocated to attempt that particular restoration task and identify the restoration interdependency. The options precedence class has the property that the implemented option (often within infrastructure B) would not be selected until some time had passed and the restoration task in the other infrastructure had still not been completed. For example, if power was out to a nursing home, the nursing home may wait some time before evacuations. Therefore, the time of the observed options precedence interdependency is often a function of the criticality of the restoration task in infrastructure B: the earliest observed ones from this class often dealt with hospitals throughout the area and how they restored their operations when faced with a lack of power (e.g., evacuating patients or setting up clinics elsewhere).

Restoration Interdependencies and Critical Infrastructure Sectors

The restoration interdependencies between the efforts of critical infrastructure sectors is important to understand in order to better plan for the level of coordination necessary for effective restoration efforts across all critical sectors after an extreme event. Table 3 presents the types of observed restoration interdependencies between infrastructures in the different 16 critical infrastructure sectors as defined in the recent presidential initiative (The

White House, Office of the President 2013). The entry in the table (Infrastructure Sector A, Infrastructure Sector B) provides all classes of restoration interdependencies between these two infrastructure sectors. For example, the entry (Energy, Transportation) lists Traditional Precedence, Effectiveness Precedence, and Competition for Resources. This implies that we observed separate incidents of a traditional precedence restoration interdependency and an effectiveness precedence restoration interdependency where an infrastructure in the Energy sector took the role of infrastructure A in the definition and an infrastructure in the Transportation sector took the role of infrastructure B. In other words, there was a situation where some task in an infrastructure in the Energy sector needed to be completed prior to starting a restoration task in an infrastructure in the Transportation sector.

For time-based restoration interdependencies, the row provides the sector of the infrastructure of a restoration task that affects the processing (either its effectiveness or starting time) of a restoration task in an infrastructure in the sector associated with the column. The Energy sector row (so it takes the role of infrastructure A) has 8 such precedence entries with other sectors: Communications, Critical Manufacturing, Emergency Services, Energy, Food and Agriculture, Government Facilities, Healthcare, and Transportation. It is also interesting to note that the Energy sector column (so it takes the role of infrastructure B in the definitions) has 4 such precedence entries. This could imply that the information from and communications with the restoration efforts of the Energy sector could be quite valuable in restoration efforts across sectors. For resource-based restoration interdependencies, the Emergency Services sector has 5 entries for the competition for resources interdependency. This sector would be heavily reliant on fuel and back-up generators to maintain its operations post-event and, therefore, would often be listed as a sector which these resources should be assigned.

DISCUSSION OF RESTORATION INTERDEPENDENCIES AND THE IMPORTANCE OF INFORMATION-SHARING

Infrastructure managers are often able to assess the damage done to their infrastructure by an extreme event and then plan their restoration efforts. Based on these planned efforts, the infrastructure manager can project out the set of operational components of their infrastructure over time or, equivalently, project out what their infrastructure will look like. This set of operational components helps to predict the level of services provided by the infrastructure; however, operational interdependencies may affect this prediction since disruptions of services in other infrastructures may affect the components of the infrastructure under consideration. Therefore, understanding these operational interdependencies can help to better predict and understand the impact of an infrastructure's restoration efforts on the services it provides to society.

In a similar manner, an understanding of restoration interdependencies can help to better predict and understand the timeline of an infrastructure's restoration efforts. Based on the planned restoration efforts, an infrastructure manager can predict the set of operational components in the infrastructure; i.e., they can predict when restoration tasks will be complete and change the set of operational components in their infrastructure. However, restoration interdependencies can impact this prediction since they can impact the planned start times of restoration tasks or impact the effectiveness of planned restoration tasks in the infrastructure under consideration.

The impact of restoration interdependencies on the effectiveness of an infrastructure's restoration efforts could potentially be mitigated through either coordination or information-sharing between infrastructures. Restoration interdependencies will still affect the timeline of an infrastructure's restoration efforts but the information-sharing would alleviate much of the uncertainty involved with the timeline. More importantly, information-sharing could help an infrastructure better formulate its restoration efforts by planning for the restoration interdependencies that will impact them. For example, an infrastructure could base its scheduling decisions (e.g., the sequencing of when crews will work on restoration tasks) on its known restoration interdependencies and when they would be alleviated. This would help to minimize 'unforced' idle time across the work crews that results in them waiting around for their next task to become available to be processed (e.g., a power crew waiting around for residential inspections to be complete) or in adapting their schedule by relocating to another task (e.g., the power work crew realizes they will sit idle and then travels to another area to work - it would have been a better use of time for the workers to go directly to this next area).

Information-sharing would be especially important in planning restoration efforts of an infrastructure that has multiple instances of the same type of restoration interdependencies with another infrastructure. As an example in the context of Hurricane Sandy, consider the subway system of New York City planning out restoration tasks to pump out water from its tunnels and stations. The pumping of a particular tunnel or station represents an options precedence relationship: the restoration task of pumping out a particular subway line requires either power to be restored to the area or a generator to be located in the area. The locations of the generators and their subsequent relocations are decisions involved in the planning of the subway system's restoration efforts. If pumps were located to pump water out of Station 1 and Station 2 and only one generator was available, information about the power restoration efforts would help plan the subway system's efforts more effectively. In particular, if both stations require the same amount of time to pump the water out, then the generator should be located at the station that will be without power for longer. Therefore, the knowledge about the power restoration efforts (i.e., which station will have power first) would aid in the restoration efforts of the subway system.

It is unlikely that full coordination could be achieved across infrastructures due to the large number of public and private-sector agencies that must formulate restoration efforts after the event. This complicates the restoration of normal day-to-day operations of society after an event like Hurricane Sandy since multiple agencies are formulating their own (independent) restoration efforts. Each agency may be working towards the goal of full restoration but the lack of communication amongst them impacts the effectiveness of the restoration as a whole. The concept of information-sharing, where certain key agencies and infrastructures share their planned restoration efforts, can help to mitigate the impacts of our identified restoration interdependencies on the overall restoration efforts since infrastructures can better plan for their impact. In addition, infrastructure managers could gain a better understanding of how the schedule of their restoration efforts impacts other infrastructure's restoration planning and could, potentially, consider altering their efforts to help other infrastructures.

An improved situational awareness of restoration interdependencies should help to improve restoration efforts (in terms of shortening restoration time) by providing a better understanding of issues that could prevent the completion of scheduled restoration tasks within an infrastructure. Infrastructure managers may need to be proactive in order to obtain the information from other infrastructures necessary for this improved situational awareness since it is unlikely that 'information-sharing' schemes would simply publicly announce planned restoration efforts. Therefore, it may be important for infrastructure managers to be proactive in terms of identifying appropriate contacts within other infrastructures in order to obtain the correct information to understand its restoration interdependencies. The time-sensitive nature of infrastructure restoration could prohibit identifying and building a level of trust with these contacts during the event and, therefore, it would be important to establish these contacts and liaisons under 'normal' conditions. It is then important for infrastructure managers to understand the improvement that could result from an improved awareness of restoration interdependencies.

Coordination and information-sharing should lead to improved restoration efforts, especially when considering restoration interdependencies. It may be important for infrastructure managers to understand the impact of a reduction in the restoration times of services in terms of measures relevant to their infrastructure. As a potential demonstration of this quantification, we can examine shifts in restoration times of power after Hurricane Sandy in New York City and Long Island. Figure 3 (created using data from New York Independent System Operator 2012) provides the power load curve of these areas during October and November

2012. The focus of the shifts for these examples is on the *percentage* of the average load that occurred after Hurricane Sandy at a particular point in time. For example, if we are looking at the time stamp of Thursday, November 1 at 2 p.m., we examine the load in New York City and compare it to the *average* load of the three previous Thursday 2 p.m. time stamps in New York City. This comparison can then help to provide the percentage of 'restored' services by Thursday, November 1 at 2 p.m. This percentage, as a function of time, will typically increase (although it is imperfect because it is a function of consumer behavior). We can then quantify the improvement in restoration by examining shifts in *when* these percentages occur. For example, if Thursday at 2 p.m. had 90% of the average load, a 15 minute shift in average restoration time would imply that Thursday at 1:45 p.m. had 90% of *its* average load the previous three weeks. A shift of 15 minutes earlier in the average restoration time results in an increase of 2356 megawatt hours (MWh) of energy over the course of the week following Hurricane Sandy in New York City. A shift of 30 minutes earlier results in an increase of 3717 MWh of energy during the same time frame. We can put these increases into the context of 'customer hours' (e.g., a customer has power for one hour) to better understand the impact; the U.S. Energy Information Administration (2011) reports that the average residential customer in 2011 in the state of New York consumes 7332 kWh of power per year. This implies that one MWh would translate to 1195 'customer hours.' Even assuming that only 50% of the increase in energy resulting from the shift goes to residential customers, the 15 minute shift would result in an increase of 1.4 million customer hours and the 30 minute shift would result in a shift of 2.2 million customer hours. This represents a significant amount of power during the city's restoration efforts. For Long Island, a shift of restoration time by 15 and 30 minutes earlier results in an increase of 1161 MWh and 1765 MWh, respectively. This translates to .69 million and 1.1 million customer hours.

The next step for research on restoration interdependencies is to attempt to more precisely *quantify* the impact of coordination and various forms of information-sharing. This will require examining models that focus on restoration efforts across infrastructures and appropriately incorporating the restoration interdependencies. The models that examine full coordination will blend the interdependent layered network model of Lee et al. (2007) that captures the performance of a set of interdependent infrastructure systems with scheduling models (such as that of Nurre et al. 2012) for each infrastructure involved in the restoration efforts. These models would help to understand the best possible performance in the restoration across infrastructures. The role of information-sharing can be captured by appropriately altering scheduling models for restoring a single infrastructure to include the impact of known disruptions (and their length) and the restoration activities of other infrastructures.

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REFERENCES

Ahuja, R.K., Magnanti, T.L., and Orlin, J.B. (1993). *Network flows: Theory, algorithms, and applications*. Prentice-Hall, Englewood Cliffs, New Jersey.

Ang, C.C. (2006). "Optimized recovery of damaged electrical power grids." M.S. thesis, Naval Postgraduate School, Monterrey, California.

Associated Press (2012). "N.Y. breweries take a hit during Hurricane Sandy." November 5, 2012. Accessed at http://www.nj.com/news/index.ssf/2012/11/ny_breweries_take_a_hit_during.html on March 14, 2013.

Barker, K. and Haimes, Y.Y. (2009a). "Assessing uncertainty in extreme events: Applications to risk-based decision making in interdependent infrastructure sectors." *Reliability Engineering and System Safety*, 94, 819–829.

Barker, K. and Haimes, Y.Y. (2009b). "Uncertainty analysis of interdependencies in dynamic infrastructure recovery: Applications in risk-based decision making." *Journal of Infrastructure Systems*, 15, 394–405.

Bernstein, N. (2012). "As students move back in, some evacuees are set adrift again." *The New York Times*. November 6, 2012. Accessed at http://www.nytimes.com/2012/11/07/nyregion/some-hurricane-sandy-evacuees-are-set-adrift-again.html on February 8, 2013.

Cagnan, Z. and Davidson, R. (2003). "Post-earthquake lifeline service restoration modeling." *Advancing mitigation technologies and disaster response for lifeline systems*, editor J.E. Beavers, American Society of Civil Engineers, 255–264.

Cavdaroglu, B., Hammel, E., Mitchell, J.E., Sharkey, T.C., and Wallace, W.A. (2013). "Integrating restoration and scheduling decisions for disrupted interdependent infrastructure systems." *Annals of Operations Research*, 203, 279–294.

Chang, S.E., McDaniels, T.L., and Reed, D.A. (2005). "Mitigation of extreme events: Electric power outage and infrastructure failure interactions." *The Economic Impacts of Terrorist Attacks*, H.W. Richardson, P. Gordon, and J.E. Moore II, eds., Edward Elgar Publishing, 70–90.

Chou, C.-C. and Tseng, S.-M. (2010). "Collection and analysis of critical infrastructure interdependency relationships." *Journal of Computing in Civil Engineering*, 24, 539–547.

Coffrin, C., Van Hentenryck, P., and Bent, R. (2011). "Strategic planning for power system restoration." *Proceedings of the International Conference on Vulnerability and Risk Analysis and Management*, 180–187.

Dueñas-Osorio, L., Craig, J.I., Goodno, B.J., and Bostrom, A. (2007). "Interdependent response to networked systems." *Journal of Infrastructure Systems*, 13, 185–194.

Flegenheimer, M. (2012). "New York subway repairs border on the edge of magic." *The New York Times*. November 8, 2012. Accessed at http://www.nytimes.com/2012/11/09/nyregion/new-york-subways-find-magic-in-speedy-hurricane-recovery.html on February 6, 2013.

Flegenheimer, M. and Leland, J. (2012). "Long gas lines, clogged roads and slim hope for a better day." *The New York Times*. October 31, 2012. Accessed at http://www.nytimes.com/2012/11/01/nyregion/new-yorkers-cling-to-hope-of-a-better-commute.html on February 6, 2013.

Goldberg, D. (2012). "With one eye on recovery from Hurricane Sandy, state keeps watch on approaching nor'easter." *The Star Ledger*. November 4, 2012. Accessed at http://www.nj.com/news/index.ssf/2012/11/with_one_eye_on_recovery_from.html on March 14, 2013.

Guha, S., Moss, A., Naor, J.S., and Schieber, B. (1999). "Efficient recovery from power outage." *Proceedings of the thirty-first annual ACM symposium on Theory of Computing (STOC)*, 574–582.

Hartocollis, A. and Bernstein, N. (2012). "At Bellevue, a desperate fight to ensure the patients' safety" *The New York Times*. November 1, 2012. Accessed at http: http://www.nytimes.com/2012/11/02/nyregion/at-bellevue-a-desperate-fight-to-ensure-the-patients-safety.html on February 7, 2013.

Heyboer, K. (2012). "Christie, Obama to visit ravaged Jersey Shore this afternoon as Sandy death toll rises." *The Star Ledger*. October 31, 2012. Accessed at http://www.nj.com/news/index.ssf/2012/10/christie_obama_to_visit_ravage.html on February 25, 2013.

Hu, W. (2012). "Cuomo waives a tax to allow docking tankers to unload their fuel more quickly." *The New York Times*. November 2, 2012. Accessed at http://www.nytimes.com/2012/11/03/nyregion/cuomo-says-gas-tankers-are-on-the-way-to-new-york.html on February 7, 2013.

Issler, M. and Brodsky, R. (2012). "Safety-check issues hamper power restoration." *Newsday*. November 10, 2012. Accessed at http://www.newsday.com/long-island/safety-check-issues-hamper-power-restoration-1.4210515 on March 14, 2013.

Johnson, B. (2012). "As Sandy's aftermath drags on, gas lines stretch through the night." *The Star Ledger*. November 1, 2012. Accessed at http://www.nj.com/news/index.ssf/2012/11/as_sandys_aftermath_drags_on_g.html on

March 14, 2013.

Lee, E.E., Mitchell, J.E., and Wallace, W.A. (2007). "Restoration of services in interdependent infrastructure systems: A network flows approach." *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, 37, 1303–1317.

Lee, E.E., Mitchell, J.E., and Wallace, W.A. (2009). "Network flow approaches for analyzing and managing disruptions to interdependent infrastructure systems." *Wiley Handbook of Science and Technology for Homeland Security*, J. G. Voeller, ed., Vol. 2, John Wiley, 1419–1428.

Lipton, E. and Krauss, C. (2012). "Military to deliver fuel to storm-ravaged region." *The New York Times*. November 2, 2012. Accessed at http://www.nytimes.com/2012/11/03/business/military-to-deliver-fuel-to-storm-region.html on February 7, 2013.

Little, R. (2002). "Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures." *Journal of Urban Technology*, 9, 109–123.

Ma, M. (2012). "Flooded and powerless, Little Ferry business owners assess the damage after Hurricane Sandy." *nj.com*. October 31, 2012. Accessed at http://www.nj.com/bergen/index.ssf/2012/10/flooded_and_powerless_little_ferry_business_owners_assess_the_damage_after_hurricane_sandy.html on February 25, 2013.

Matisziw, T.C., Murray, A.T., and Grubesic, T.H. (2010). "Strategic network restoration." *Networks and Spatial Economics*, 10, 345–361.

Matisziw, T.C., Murray, A.T., and Grubesic, T.H. (2009). "Exploring the vulnerability of network infrastructure to disruption." *Annals of Regional Science*, 43, 307–321.

McDaniels, T.L., Chang, S.E., Peterson, K., Mikawoz, J., and Reed, D.A. (2007). "Empirical framework for characterizing infrastructure failure interdependencies." *Journal of Infrastructure Systems*, 13, 175–184.

McDaniels, T.L., Chang, S.E., and Reed, D.A. (2009). "Characterizing infrastructure failure interdependencies to inform system risk." *Wiley Handbook of Science and Technology for*

Homeland Security, J. G. Voeller, ed., Vol. 2, John Wiley, 1–16.

Mendonca, D. and Wallace, W.A. (2006). "Impacts of the 2001 World Trade Center attack on New York City critical infrastructures." *Journal of Infrastructure Systems*, 12, 260–270.

New York Independent System Operator (2012). *Real-Time Actual Load.* Retrieved from http://www.nyiso.com/public/markets_operations/market_data/custom_report/index.jsp ?report=rt_actual_load.

Nurre, S.G., Cavdaroglu, B., Mitchell, J.E., Sharkey, T.C., and Wallace, W.A. (2012). "Restoring infrastructure systems: An integrated network design and scheduling problem." *European Journal of Operational Research*, 223, 794–806.

Ouyang, M. (2014). "Review on modeling and simulation of interdependent critical infrastructure systems." *Reliability Engineering and System Safety*, 121, 43–60.

Ouyang, M. and Dueñas-Osorio, L. (2011). "Efficient approach to compute generalized interdependent effects between infrastructure systems." *ASCE Journal of Computing in Civil Engineering*, 25, 394–406.

Pinedo, M.L. (2012). *Scheduling: Theory, Algorithms, and Systems.* Springer, New York, New York.

Reed, D.A., Preuss, J., and Park, J. (2006). "Context and resiliency: Influences on electric utility lifeline performance." *Infrastructure Risk Management Processes: Natural, Accidental, and Deliberate Hazards*, C. Taylor and E. VanMarcke, eds., ASCE Publications 118–144.

Rinaldi, S. M., Peerenboom, J. P., and Kelly, T. K. (2001). "Identifying, understanding, and analyzing critical infrastructure interdependencies." *IEEE Control Systems Magazine*, 21(6), 11–25.

Santora, M. (2012). "City's transit and power slowly return." *The New York Times.* November 3, 2012. Accessed at http://www.nytimes.com/2012/11/04/nyregion/power-returns-to-lower-manhattan.html on March 2, 2013.

Schwartz, N. (2012). "After storm, businesses try to keep moving." *The New York Times.*

October 30, 2012. Accessed at http://www.nytimes.com/2012/10/31/business/after-hurricane-sandy-businesses-try-to-restore-service.html on February 6, 2013.

Shoji, G. and Toyota, A. (2009). "Modeling of restoration process associated with critical infrastructure and its interdependency due to a seismic disaster." *TCLEE 2009: Lifeline earthquake engineering in a multihazard environment*, 647–658.

Star Ledger Staff (2012). "Hurricane Sandy leaves N.J., but destruction, questions remain." *The Star Ledger*. October 30, 2012. Accessed at http://www.nj.com/news/index.ssf/2012/10/hurricane_sandy_leaves_nj_but.html on March 2, 2013.

Stein, R. (2012). "Cell phone service spotty, but Verizon Wireless says it's working on it." *The Jersey Journal*. November 2, 2012. Accessed at http://www.nj.com/hudson/index.ssf/2012/11/verizon_working_hard_to_get_al.html on March 14, 2013.

Stilp, M., Carbajal, A., Ergun, O., Keskinocak, P., and Villarreal, M. (2012). "Debris clearance operations." School of Industrial and Systems Engineering, Georgia Institute of Technology.

United States Department of Energy, Office of Energy Delivery and Reliability (2012). "Hurricane Sandy situation reports." Accessed at http://www.oe.netl.doe.gov/named_event.aspx?ID=67 on May 29, 2013.

United States Energy Information Administration (2011). "How much electricity does an American home use?" March 13, 2013. Accessed at http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3 on June 10, 2013.

Wallace, W.A., Mendonca, D., Lee, E.E., Mitchell, J.E., and Chow, J. (2003). "Managing disruptions to critical interdependent infrastructures in the context of the 2001 World Trade Center attack." *Beyond September 11th: An Account of Post-Disaster Research*, 165–198.

The White House, Office of the President (2013). "Presidential policy directive - Critical infrastructure security and resilience."

Winkler, J., Dueñas-Osorio, L., Stein, R., and Subramanian, D. (2011). "Interface network models for complex urban infrastructure systems." *Journal of Infrastructure Systems*, 17, 138–150.

Xu, N., Guikema, S.D., Davidson, R.A., Nozick, L.K., Cagnan, Z., and Vaziri, K. (2007). "Optimizing scheduling of post-earthquake electric power restoration tasks." *Earthquake Engineering and Structural Dynamics*, 36, 265–284.

Yan, S. and Shih, Y.-L. (2009). "Optimal scheduling of emergency roadway repair and subsequent relief distribution." *Computers & Operations Research*, 36, 2049–2065.

Zdan, A. (2012). "Mercer county power outage number down to 33,000, with two trenton senior complexes restored." *The Times*. November 2, 2012. Accessed at http://www.nj.com/mercer/index.ssf/2012/11/hurricane_sandy_mercer_power_out_update .html on March 14, 2013.

	Residential	Telecommunications	Wireless Telecommunications	Commercial Supply Chain	Emergency (EMS) Services	Emergency (Fire) Services	Emergency (Police) Services	Emergency Shelters	Public (EOC) Services	Fuel Supply Chain	Natural Gas	Power	Necessity (Food) Supply Chain	Public (Education) Services	Hospital	Senior Care Facilities	Port System	Road System	Subway	Water	Waste Water
Residential												TR(9)									
Telecommunications										CR		TR									
Wireless Telecommunications																					
Commercial Supply Chain				OP																	
Emergency (EMS) Services												CR									CR
Emergency (Fire) Services	OP																				
Emergency (Police) Services													CR			CR					
Emergency Shelters														CR(3)							
Public (EOC) Services																					
Fuel Supply Chain		CR		OP						OP(2)						OP					
Natural Gas																		TR			
Power	OP	TR(3)	TS(2)	TR, TS(2)	CR				EF	TR(3), OP(2)			TR, EF, TS		OP(4)	OP(5)		TR(6), EF(2), CR	TR, EF		CR
Necessity (Food) Supply Chain							CR									CR					
Public (Education) Services								CR(3)													
Hospital															OP(4)						
Senior Care Facilities							CR						CR			OP(4)					
Port System										TR(7), OP(1)											
Road System	TR, OP, TS(6)			TR		TR					TR	TR(8), CR									
Subway																					
Water															CR						CR
Waste Water					CR							CR	CR							CR	

TABLE 1. Observed Restoration Interdependencies across Infrastructures. The rows correspond to infrastructure A and the columns to infrastructure B in the definitions. The meanings of the entries are TR - Traditional, EF - Effectiveness, OP - Options, TS - Time-Sensitive, and CR - Competition for Resources. A number inside the () indicates the number of the multiple observations of that restoration interdependency and pair of infrastructures.

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TABLE 2. Frequency of Classes of Restoration Interdependencies

	NYT	Newsday	Star Ledger	Other NJ	PI	Total
Traditional Precedence	14	8	10	11	2	45
Effectiveness Precedence	3	0	1	1	0	5
Options Precedence	4	2	1	8	0	15
Time-Sensitive Options	2	1	4	4	0	11
Competition for Resources	3	1	1	2	1	8
Total	26	12	17	26	3	84

	Chemical	Commercial Facilities	Communications	Critical Manufacturing	Dams	Defense Industrial Base	Emergency Services	Energy	Financial Services	Food and Agriculture	Government Facilities	Healthcare	Information Technology	Nuclear	Transportation	Water and Waste Water
Chemical																
Commercial Facilities								TR								
Communications								TR, CR								
Critical Manufacturing				OP												
Dams																
Defense Industrial Base																
Emergency Services							OP	CR		CR	CR	CR				CR
Energy			TR, TS	TR, OP			OP, CR	TR, OP		TR, EF, TS	OP	OP			TR, EF, CR	CR
Financial Services																
Food and Agriculture							CR									
Government Facilities							CR				OP					
Healthcare							CR			CR						
Information Technology																
Nuclear																
Transportation		TS		TR			TR	TR, OP, CR								
Water and Wastewater							CR	CR								

TABLE 3. Observed Restoration Interdependencies in Critical Infrastructure Sectors. The rows correspond to infrastructure A and the columns to infrastructure B in the definitions. The meanings of the entries are TR - Traditional, EF - Effectiveness, OP - Options, TS - Time-Sensitive, and CR - Competition for Resources.

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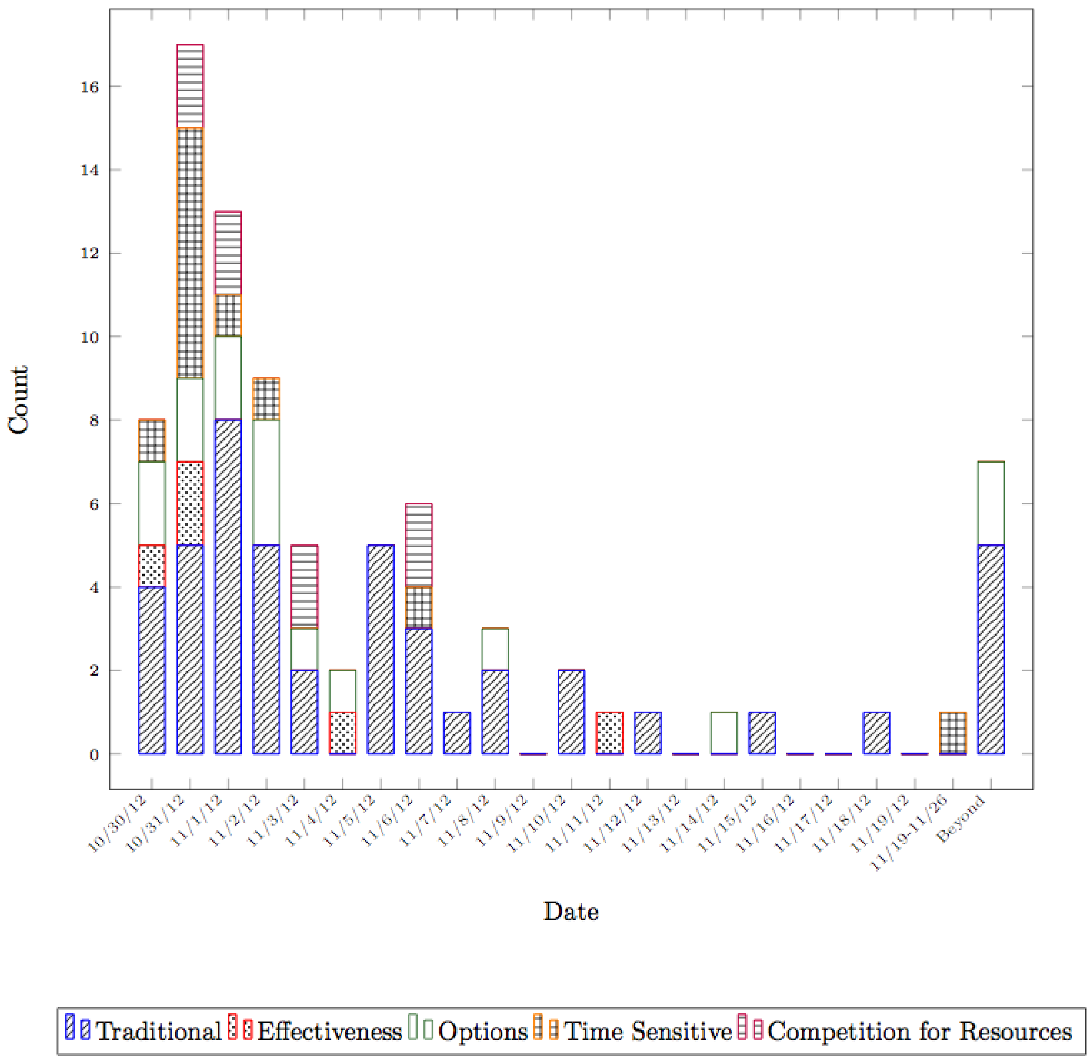

FIG. 1. Timeline for the Observed Restoration Interdependencies.

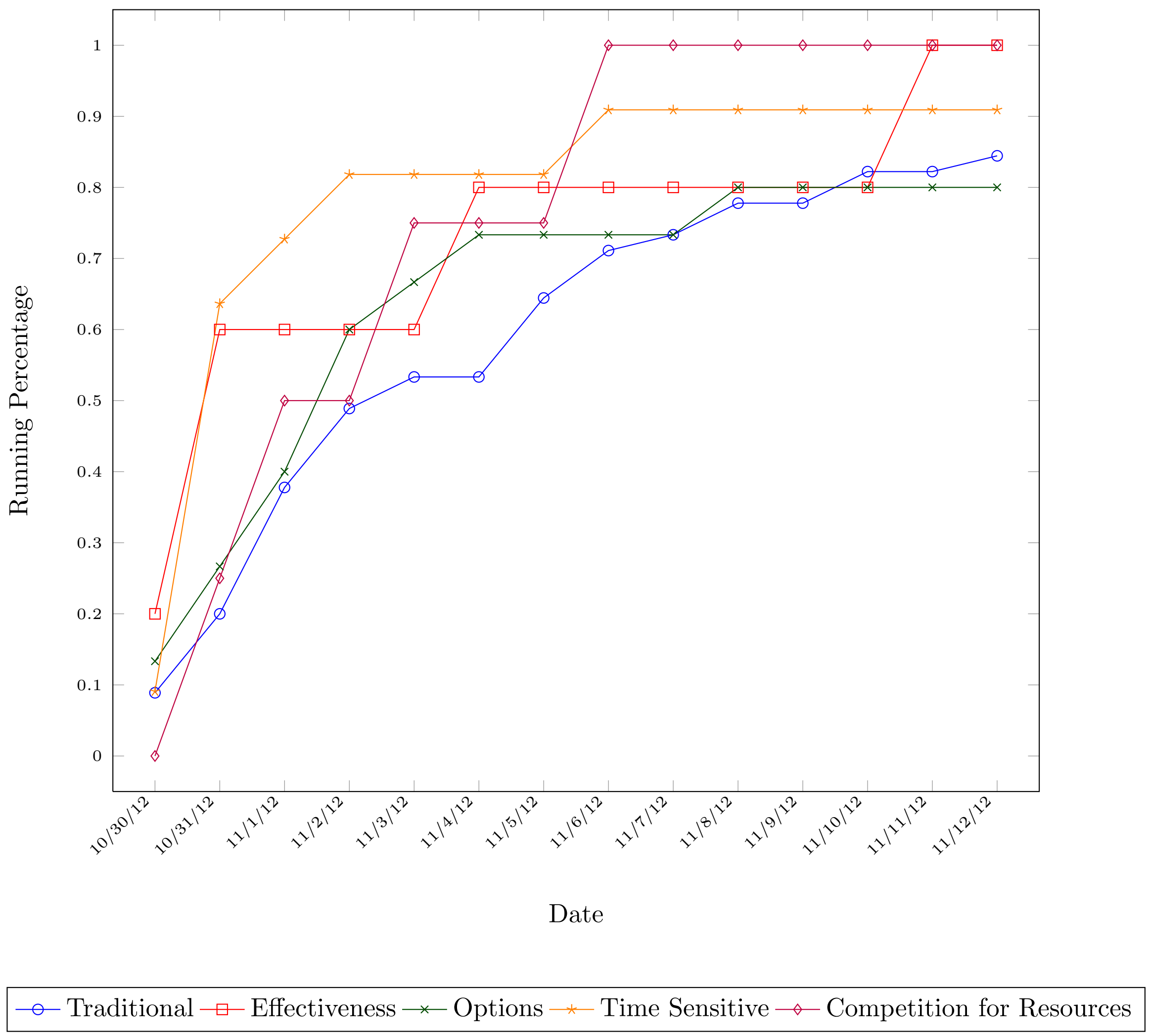

FIG. 2. Timeline for the percentage of total observed restoration interdependencies of a class by a certain date.

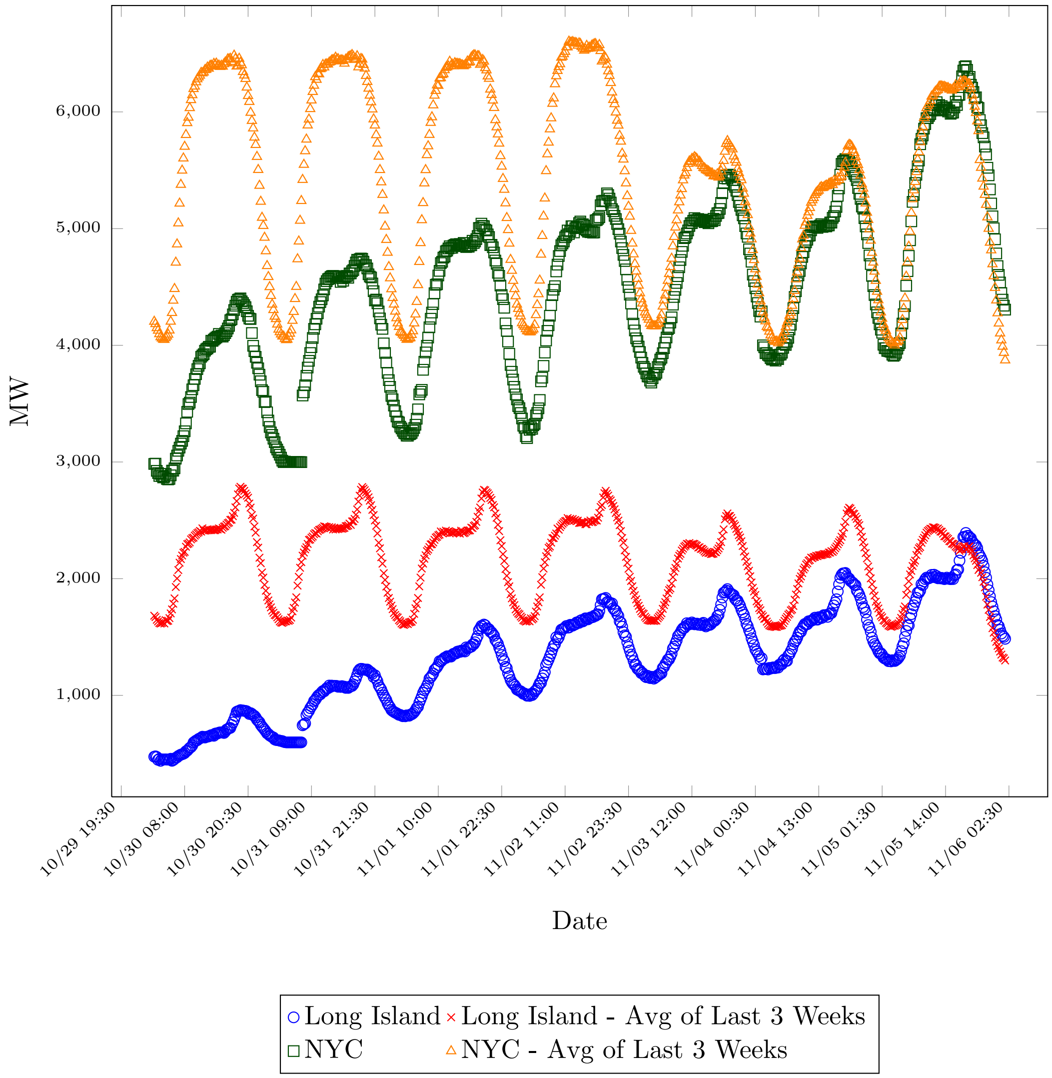

FIG. 3. The power load curves for New York City and Long Island during October and November 2012.