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 in their restoration efforts after an extreme event. Restoration interdependencies occur whenever a restoration task in one infrastructure is impacted by restoration efforts in another infrastructure. This work identifies examples of observed restoration interdependencies in 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 they were observed, the infrastructures involved with the restoration interdependency, and discussing their potential impact on infrastructure restoration.

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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 signifianct 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. 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 components is delayed due to the unavailability of roads (or, equivalently, lack of restoration) in the road network. This work: (i) identifies the 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.

The concept of *operational interdependencies* between critical infrastructure 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. For example, disruptions in the power infrastructure could prevent a subway system from running all its scheduled routes, thereby disrupting transportation services provided by the subway. 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. Our work presents a similar overview of restoration interdependencies observed after Hurricane Sandy in the New York and New Jersey areas.

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 interdependendent 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. The distiniguishing characteristic of restoration interdependencies is that there is a distinct *temporal element* associated with them since they focus on the restoration efforts of the systems as opposed to the consequences of an initial infrastructure failure.

The focus of this paper is on *restoration interdependencies* between infrastructure systems after an extreme event. An *infrastructure* is broadly defined 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 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 line with the recent presidential initiative (The White House, Office of the President 2013) that defines 16 critical infrastructure sectors including ones with both civil (e.g., Transportation) and social (e.g., Healthcare) components. It is important to note that our work focuses on *specific infrastructures* within each sector rather than the sector as a whole (e.g., power instead of 'Energy'). The Appendix includes a list of infrastructures that were observed to be involved in a restoration interdependency, broked down by the sector to which they belong.

The most basic type of restoration interdependency is related to the concept of operational interdependencies: a restoration task in an infrastructure relies on the services provided by another infrastructure. For example, after Hurricane Sandy, power was needed to pump out flooded subway stations in Manhattan. The pumps required power to operate, which could be supplied by either the power system or a portable generator. If power was available to an area where the pump was located, then this restoration task for the subway system could be conducted as planned. This type of interdependency is important in the sense that it bridges the gap between operational interdependencies and restoration interdependencies that link the restoration efforts of multiple infrastructures. However, it is unlikely that this interdependency would often be reported because it only affects a task in an infrastructure's restoration efforts when the required service is disrupted. This latter situation is more important since it links the restoration efforts across multiple infrastructures. In particular, the service must be restored in infrastructure A before the task in infrastructure B can be started. Therefore, the focus of our work will be on situations when restoration tasks across infrastructures are linked in terms of precedence or resource considerations.

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), 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.

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 qualitiative 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.

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 of a restoration task meaning any task, process, or activity that is done in order to restore an infrastructure back to normal operating conditions (or an equivalent state). It is important to note that when a restoration task (such as pumping out a flooded subway tunnel) of an initial infrastructure requires the disrupted services provided by another infrastructure (such as power), this situation constitutes a restoration interdependency. This is because the timing of the restoration task in the initial infrastructure is impacted by when the restoration of services to the impacted area is completed by the other infrastructure. The key aspect of this situation for it to be classified as a restoration interdependency is that *the restoration efforts* of the initial infrastructure are impacted by the disruption of services and, equivalently, the timing of the restoration of these services by the other infrastructure.

Restoration interdependencies can, to a certain extent, link the restoration efforts of multiple infrastructures. Therefore, the schedule of restoration efforts of an infrastructure may be impacted by its restoration interdependencies. For example, a precedence interdependency may force a scheduled restoration task in an infrastructure to be delayed since a restoration task in another infrastructure needs to be completed beforehand. 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 the restoration interdependencies may help to better understand the level of communication and/or coordination required across sectors in responding to an extreme event.

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 intedependencies* (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 but not a restoration interdependency. The focus of this section is to present some examples, in the context of Hurricane Sandy, to illustrate these differences.

For example, 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. Therefore, 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 constitues an infrastructure failure interdependency since the initial failure in the power infrastructure caused a failure in the subway system. This would not constitute a restoration interdependency because there were no restoration tasks in the subway system that were dependent on power.

However, there were restoration tasks in the subway system after Hurricane Sandy that were dependent on power. For example, Flegenheimer (2012) discusses that test trains needed to be run in the subway system prior to running scheduled routes (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 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 the which infrastructure needs to complete a task before the pumping task can begin.

As previously noted, the 'simplest' class of restoration interdependencies is when a restoration task in an infrastructure requires the *services* provided by another infrastructure. This class will not be as frequently reported (if at all) since the restoration task goes off without any delay if the required services are available. Therefore, this work focuses on situations where restoration tasks and efforts are linked across multiple infrastructures. The most common situation that was observed for this simple class is when a restoration task within an infrastructure required the services provided by 'first-responder' infrastructures such as the police, fire, and EMS infrastructures. For example, police escorted power crews during their restoration activities to prevent harassing behavior (Santora 2012), were posted at intersections whose lights were out to help the operations of the road network, and were posted at gas stations in New Jersey and New York as they re-opened to control the lines and the crowds. These activities should be viewed as part of the services provided by the police infrastructure since their daily operations are focused on the safety of citizenry and maintaining order. Similarly, firefighters needed to respond to fires caused by the event, help people evacuate areas that were subjected to severe flooding, and perform search and rescue missions as part of their 'normal' operations.

It is also important to note that during the initial aftermath of an event like Hurricane Sandy, people are searching for relevant information about the effects of it. Therefore, trusted news sources, such as newspapers and other reputable agencies, can help deliver this information to the local population, including delivering outage information to other infrastructures. However, these news sources can also suffer from this simplest class of restoration interdependencies. Without power, The Star Ledger, the main newspaper in New Jersey, was not able to print and its updates to its webpage came through "dictacting stories to sister papers across the country" (Star Ledger Staff 2012). This means that the service provided by The Star Ledger would have been more effectively provided had power been restored to its main offices.

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 of them. 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 are: 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 other 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, quotes were identified that discussed potential restoration interdependencies. If quotes 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 Recovers" 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 quotes were collected from 175 articles. A coding scheme was developed to then classify different types of restoration interdependencies. We note that not all quotes ended up concerning a restoration interdependency, so they were omitted from our observations. This was often due to the quote discussing an operational interdependency (e.g., a subway line was not running due to lack of power) as opposed to a restoration interdependency. We also note that multiple quotes may be associated with the same incident reported on by different sources. Using the coding scheme, a person classified all quotes into different classes of restoration interdependencies (including a 'not relevant' classification) resulting in a total of 96 quotes dealing with observed restoration interdependencies. Another person went through a random sampling of 10% of the quotes 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. A full list of infrastructures and their breakdown by critical infrastructure sectors appears in the Appendix.

Traditional Precedence

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

Observed Frequency: 48.

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 were 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 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: 8.

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 drain floodwaters from a road (Ma 2012).
- (Telecommunications, Fuel Supply Chain). Gas stations can only accept cash from customers due to disruptions with their credit card lines and communications systems (Hu and Yee 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 infrastructue A can take a variety of forms. We observed situations where the processing time of a restoration task would decrease and situations where a restoration task would be made simpler (e.g., a gas station accepting both credit cards and cash) 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: 20.

Examples (A_1, A_2, B):

- (*Power, Hospital*, Hospital). Bellevue Hospital lost both power and its backup generators, but still needed to provide comfort and safety for its patients; 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).

- (*Port System, Fuel Supply Chain*, Fuel Supply Chain). The distribution of gas to restore normal levels of reserves at gas stations can be accomplished by either repairing terminals and ports or dispatching trucks from out of state into the area (Hu and Krauss 2012).
- (*Power, Fuel Supply Chain*, Fuel Supply Chain). A gas station could reopen by either having its power restored or receiving a generator (Goldberg 2012).

Discussion: Many of the observed options restoration interdependencies typically involve how infrastructure B can deal with the disruption in services of another infrastructure. 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 reopen. 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 another 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.

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 (EMS) Services, Power). Emergency vehicles and power restoration crews both require fuel to aid their restoration activities (Nussbaum 2012).
- (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 providing 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. First, the frequency of such restoration interdependencies (as observed by the number of quotes found in articles discussing them) are provided. 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 16 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 96 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 discussed in the newspapers (48 instances); the options precedence restoration interdependency (20 instances) was the next most frequently reported.

Temporal Analysis

This section focuses on the temporal analysis of the observed restoration interdependencies. Figure 1 provides a timeline 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 has focused on October 29, 2012 and 83 of 96 (86.5%) observed restoration interdependencies were reported during these first two weeks. It should be noted that many of the other 13 articles not covered in this figure 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 18 which were reported two days after the storm (on October 31, 2012) and the following day 16 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 Hurricane Sandy.

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 has 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 or to a gas station, the nursing home or gas station may wait some time before evacuations (in the case of the nursing home) or obtaining a back-up generator (in the case of the gas station). 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 the 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 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 infrastruture in the Energy sector needed to be completed prior to starting a restoration task in an infrastructure in the Transportation sector. In addition, we observed that a restoration task in an infrastructure in the Energy sector and a restoration task in an infrastructure in the Transportation sector competed for the same resource.

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, there is no particular sector that stands out in terms of their observed resource relationships with other infrastructures.

DISCUSSION OF RESTORATION INTERDEPENDENCIES AND THE IMPORTANCE OF INFORMATION-SHARING

Infrastructure managers are 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 lower Manhattan 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.

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.

These forms of coordination and information-sharing should lead to improved restoration efforts, especially when considering restoration interdependencies. As a potential quantification of this improvement, we can examine shifts in restoration times of services provided by infrastructures after Hurricane Sandy. As our first example, we focus on power restoration in New York City and in 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 customer hours and 1.1 million customer hours.

The second example in quantifying the improvement in restoration efforts through coordination or information-sharing is on the fuel supply chain. Major aspects of the restoration efforts of the fuel supply chain were ensuring that demand could be met at gas stations and appropriate inventory levels were reestablished after Hurricane Sandy. The U.S. Energy Information Administration (2012) provides a report on surveys of gas stations in the New York metropolitian area and the results suggest that disruptions to the supply of fuel was a significant reason for gas stations to be closed. The focus of this quantification is on shifting the restoration times of the *refineries* that feed the New York metropolitian area earlier. The United States Department of Energy Delivery and Reliability 2012 provides frequent reports about the status of all energy-related infrastructures and, in particular, the status of the 6 refineries in the area affected by Hurricane Sandy. The statuses that were reported are: 'Shut Down' (zero capacity), 'Reduced Runs' (which we assumed to be operating at 50% capacity), and 'Normal' (assumed to be operating at 100% capacity). These reports were in half-day increments and we focus on shifting the status of the refinery by a half day earlier when shifting restoration efforts earlier. This may be an unrealistic shift but was the best estimate that could be achieved due to the timing of the reports. This half-day restoration shift results in an increase of 131,800 barrels coming into the area over the course of the week following Hurricane Sandy. Given the demand for fuel after Hurricane Sandy, this increase would have helped the area in its restoration.

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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APPENDIX

The purpose of this section is to provide the list of infrastructures that were observed to be involved in a restoration interdependency. This list of infrastructures is broken down by critical infrastructure sector, i.e., each infrastructure within a certain sector is presented in the same section.

Commercial Facilities Sector

Commercial Facilities

Residential

Communications Sector

Telecommunications

Wireless Telecommunications

Critical Manufacturing Sector

Commercial Supply Chain

Emergency Services Sector

Emergency (EMS) Services

Emergency (Fire) Services

Emergency (Police) Services

Emergency Shelters

Public (Emergency Operations Center) Services

Energy Sector

Fuel Supply Chain

Natural Gas Infrastructure

Power

Financial Services Sector

Financial Services

Food and Agriculture Sector

Necessity (Food) Supply Chain

Government Facilities Sector

Public (Education) Services

Healthcare Sector

Hospital

Senior Care Facilities

Transportation Sector

Port System

Road System

Subway

Water and Wastewater Sector

Water

Waste Water

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

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TABLE 2. Frequency of Classes of Restoration Interdependencies

	NYT	Newsday	Star Ledger	Other NJ	PI	Total
Traditional Precedence	16	9	10	11	2	48
Effectiveness Precedence	5	0	1	2	0	8
Options Precedence	6	2	2	10	0	20
Time-Sensitive Options	2	1	4	4	0	11
Competition for Resources	3	1	1	2	2	9
Total	32	13	18	29	4	96

	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	OP							
Communications				EF				TR, EF, CR		EF						
Critical Manufacturing				OP												
Dams																
Defense Industrial Base																
Emergency Services							OP	CR		CR	CR	CR				CR
Energy			TR, TS	TR, OP			TR, OP, CR	TR, OP		TR, EF, TS	TR, OP	OP			TR, EF, CR	CR
Financial Services									OP							
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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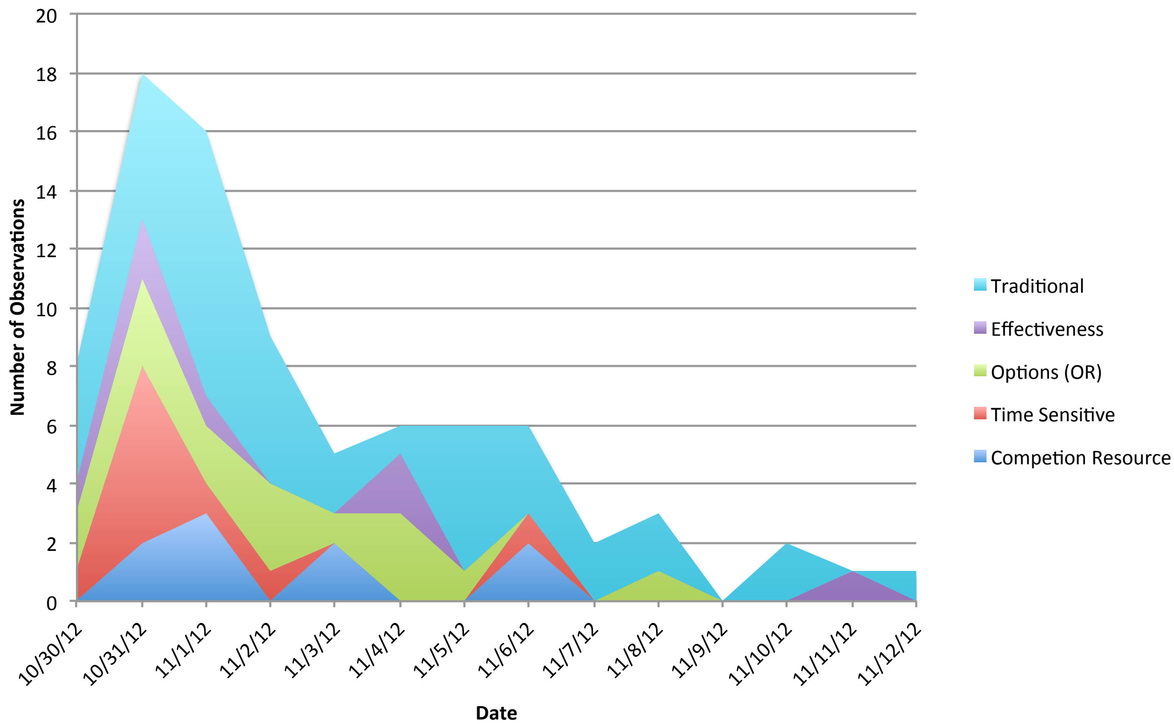

FIG. 1. Timeline for the Observed Restoration Interdependencies.

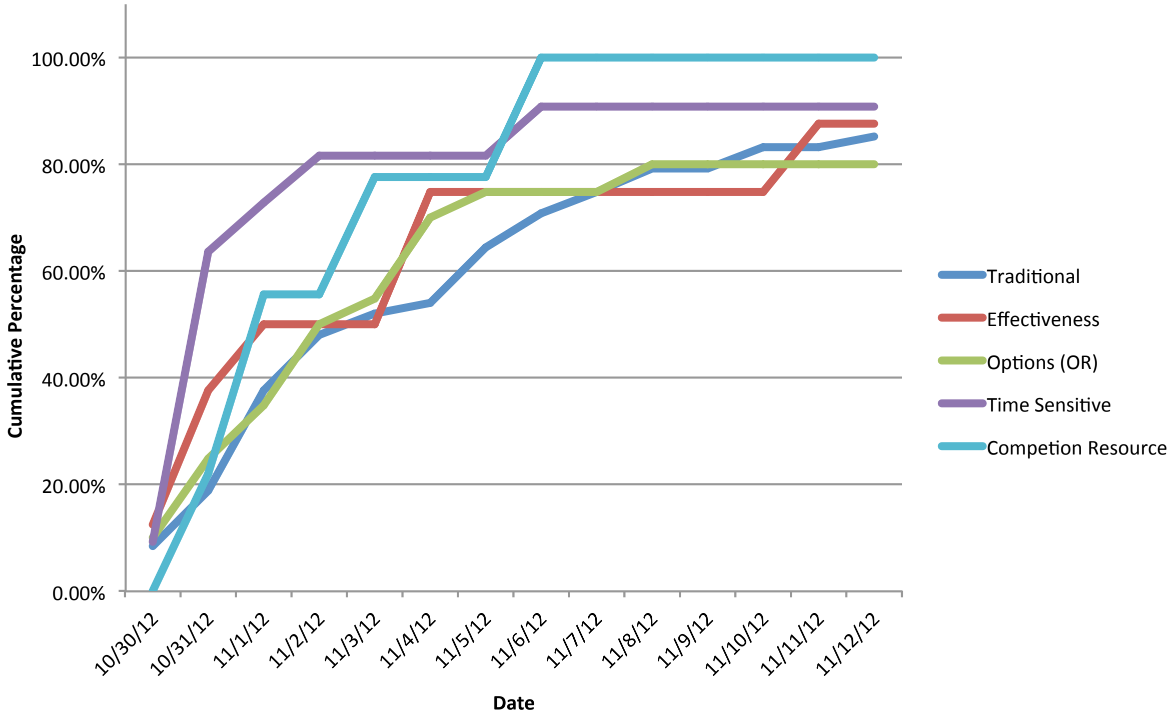

FIG. 2. Timeline for the percentage of total observed restoration interdependencies of a class by a certain date.

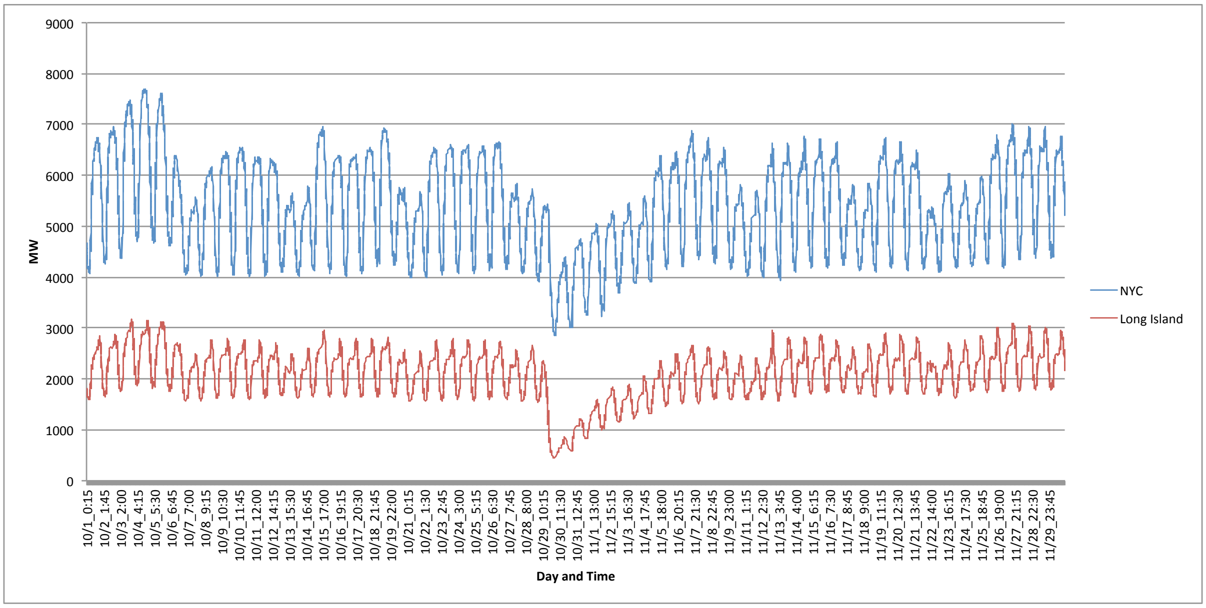

FIG. 3. The power load curves for New York City and Long Island during October and November 2012.