Identifying and Modeling the Interdependencies of Restoration Efforts across Infrastructures

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The purpose of this work is to explore the new concept of *restoration interdependencies* that exist between infrastructures during their restoration efforts from an extreme event, such as Hurricane Sandy that affected areas in and around New Jersey, New York City, and Long Island in late October 2012. Restoration interdependencies occur whenever a restoration task, process, or activity in one infrastructure is impacted by a restoration task, process, or activity in another infrastructure. As an example, debris 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 in the road network. The purpose of this project is to: (i) identify the frequency of such restoration interdependencies as reported through major newspapers in the areas affected by Hurricane Sandy, (ii) provide a classification scheme for restoration interdependencies, (iii) investigate, through interviews with infrastructure managers, their impact on infrastructure restoration after Hurricane Sandy, and (iv) provide models to understand the impact of them on post-event decision-making in infrastructure restoration.

The concept of *operational interdependencies* between critical infrastructures has been well-studied and occur when a component of one infrastructure requires services provided by another infrastructure in order to properly function. 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 can cause a disruption of subway services. Subway services would then not be restored until power restoration work crews repair the damaged substation. However, after Hurricane Sandy, there were restoration tasks in the subway system that were dependent on power. For example, the running of trains to test repairs done in the subway system and the pumping out of floodwaters from subway tunnels required power. The running of test trains represents a *traditional precedence* restoration interdependency in that the restoration task in the subway could

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not begin until a restoration task (the repairs to the substation) were complete. The restoration task of pumping out floodwaters represents an *options precedence* in that a restoration task in either the power system (repairs to the substation) or a task in the subway system (bringing in a portable generator) needed to be complete before the floodwater removal task could begin.

Our work to date has focused on identifying and classifying restoration interdependencies. The identification process involved reviewing articles related to Hurricane Sandy from major newspapers in the affected areas including: The New York Times (New York City), Newsday (Long Island), The Star Ledger (New Jersey), and The Philadelphia Inquirer (South New Jersey and Philadelphia). Based on quotes from articles identified in this process, a classification scheme was developed which includes five distinct classes of restoration interdependencies: traditional precedence, effectiveness precedence, options precedence, time-sensitive options, and competition for resources. The definitions of these classes are:

- **Traditional Precedence**: A restoration task in infrastructure B cannot be started until a restoration task in infrastructure A is complete.
- **Effectiveness Precedence**: 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.
- **Options Precedence**: 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.
- **Time-Sensitive Options**: 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.
- **Competition for Resources**: Restoration tasks in infrastructures A_1, A_2, ..., A_n compete for the same set of scarce resources.

An analysis of the types of infrastructures involved in these restoration interdependencies and a timeline for their occurrence was conducted. Infrastructures within the energy sector, in particular, the electric power infrastructure and the fuel (gasoline and diesel) supply chain, were invovled in the largest number of observed restoration interdependencies. This could imply that information from and communications with these infrastructures could be quite valuable in mitigating the impact of restoration interdependendences in infrastructure restoration after extreme events.

Given the frequency of which restoration interdependencies arose with the electric power system, one next step for the project is to discuss power restoration efforts after Hurricane Sandy with emergency managers from various power companies. This will help to investigate the impact of restoration interdependencies on decision-making after the event and, potentially, identify any

existing coordination mechanisms in place to help mitigate their impact on infrastructure restoration. Another planned direction for this project is to expand recent research on network design and scheduling models on infrastructure restoration to multiple interdependent infrastructure systems. These new scheduling models will specifically recognize the restoration interdependencies between these systems and will allow for an understanding on how different coordination mechanisms and information-sharing across organizations can lead to improved effectiveness in restoration efforts.