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Planning resilient motor-fuel supply chain

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ABSTRACT

Two major extreme-weather events occurred in New York State between 2011 and 2012. Each with the odds of a 100-year occurrence suggesting that such extreme events are the region's "new normal." City and state policy-makers, in response, are studying how to develop a network of robust, resilient critical infrastructure facilities. These studies, however, typically fail to address interdependencies among critical infrastructures and lack a quantitative tool to investigate the maximum resilience possessed by a given infrastructure facility in the face of climate-change-induced hazards.

We propose a multi-stage stochastic mathematical program to maximize network resilience given: *i*) random arrival of extreme events; *ii*) the network's inherent capacity to withstand and cope with the aftermath of exogenous shocks; *iii*) pre-, during-, and post-event strategies available to enhance system operability; and *iv*) budgeting and technological restrictions facing policy-makers.

Our approach allows both qualitative and quantitative paradigms to interact. Our model thus clarifies how to allocate resources proactively and how the network's absorptive, adaptive, and restorative capacities can be coordinated to enhance overall system resilience. Our findings suggest that an integrated planning approach combined with smart allocation of resources across a network's main elements creates a greater degree of resilience while utilizing less costly resilience-enhancing strategies.

1. Introduction

New York City's (NYC) vulnerability to Atlantic hurricanes and tropical storms caused numerous facility failures resulting in considerable economic harm at both the regional and national levels. Hurricane Sandy, for example, battered the NYC's critical transportation facilities with heavy rain, strong winds, and a record storm surge. Many networks experienced major interruptions. The City's motor-fuel supply chain (FSC) encountered extensive, serious disruptions: refineries and terminals lost power and were damaged, pipelines and power grid were shut down, which led to widespread gas station closures. Despite early speculation that such closures were due primarily to power outages affecting the pumping of gas, the larger problem was that stations simply had no gas to pump. According to the U.S. Energy Information Administration (EIA) [10], after ten days following the Sandy, more than one-fifth of gas stations across the New York City metropolitan area -and a larger ratio in Manhattan- had no gasoline available for sale [22]. The post-Sandy supply deficit was caused by inoperability in motor-fuel facilities key-elements. Sandy affected a total of twenty-eight terminals. Additionally, thousands of roads were closed due to downed power lines and tree limbs that hampered trucks in getting to open terminals for fuel deliveries, even if fuel was obtainable [20]. Station closures – and the long lines at stations with gas – limited mobility and slowed economic activity while hampering recovery efforts. This caused cascading failures across other critical facilities such as transportation and transit.

In response, New York State (NYS) announced the appointment of three commissions -NYS 2100, NYS Respond, and NYS Ready- to "improve the State's emergency preparedness and response capabilities and strengthen the State's infrastructure to withstand natural disasters" [9]. Commission reports were released within a year after super-storm Sandy. They recognized that NYC's motor-fuel infrastructure was a critical yet vulnerable network, in need of a resilient platform to better withstand anticipated extreme weather events. Following that recognition, a large number of risk assessment and disaster preparedness studies were undertaken to analyze the functionality of NYC's critical infrastructure facilities when stressed or under attack. Despite such intensive study, modeling this problem - likewise modeling many

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problem sets featuring system of systems (SOSs) aspects - remains challenging and complex [4].

There are several sources of such complexity, however. First, major urban infrastructure facilities are inherently complex. Many urban infrastructures, are complex to design and operate due to their large size combined with dynamic time-variant behavior, heterogeneity within end-users, and extensive interdependencies with other critical facilities. Second, a majority of urban America's infrastructures are nearing the ends of their service lives, according to American Society of Civil Engineers (ASCE) [2]. Aging and often over-utilized facilities introduce new types of operational difficulties, when infrastructures nominal service rate is either unachievable or not adequate. Third, many urban facilities are vulnerable to whether man-made or natural, sudden extreme events. Both direct inoperability imposed by extreme exogenous shocks (e.g., terrorist attacks, severe weather episodes), as well as indirect failures caused by facility interdependence, can result in failures across network elements. Any source of complexity introduces new challenges to facility designer and operators. They must be willing to both optimize a facility's functionality in the state of 'business as usual' (BAU) while protecting and maintaining the facility's integrity under an extreme event.

We address this challenge by applying the concept of network resilience to the motor-fuel supply chain management. Following Turnquist et al. (2013), we develop a mathematical program to analyze practical strategies for the allocation of resources that maximizes Manhattan FSC's resilience during hurricanes. Those strategies are complementary, and are developed within three aspects of resilience: absorption, adaptation, and restoration. Resilience-enhancing strategies (RES) can be implemented pre-, during-, and post-event(s) to effectively manage inoperability created by severe weather episodes. Uncertainty regarding the timing of such extremes, with the decoupling of pre-event investments and post-event network performance, suggests the use of a stochastic bi-stage optimization model. The fuel replenishment and distribution tasks (i.e. second stage variables) are here conditioned on investment decisions made in the first stage. The model describes an optimal investment strategy that ensures maximum FSC resilience under extreme weather events.

2. Literature review

Holling [11] defined resilience as a "measure of the persistence of systems." That concept has been applied in a number of disciplines, including economics, politics, engineering, and planning. In supply-chain and risk management studies, however, resilience is defined as a system-wide property encompassing various characteristics. The characteristics that have been suggested are broad. Lee [16] described the key aspects of supply-chain resiliency as agility, adaptability, and alignment. Bruneau et al. [6] suggested four complementary measures including robustness, redundancy, resourcefulness, and speed of recovery. Ponomarov and Holcomb [33] further included readiness, response, and recovery, while Soni and Jain [41] added flexibility, visibility, collaboration, adaptability, and sustainability as required attributes leading to supply-chain resilience. Finally, Turnquist and Vugrin [48] explored the concept of resilience in the supply-chain domain. They considered resilience-enhancing investments through their impact on the absorption, adaptation, and restoration dimensions.

Despite the 'divergent definitions' and 'conceptual vagueness' of the term resilience [14,44,46], commonalities include: i) resilience, which is the capability of infrastructure systems to experience minimum inoperability in time of disaster and recover optimally into the pre-disturbance state, and ii) resilience-enhancing strategies are conceptualized within three time windows of pre-, during- and post-shock. Relying on existing literature, we view "resilience" as a system's ability to better withstand and absorb, efficiently adapt to, and quickly/cheaply recover from, inoperability imposed by extreme events. In addition to illustrative and conceptual studies, a number of quantitative methods have been developed to address the resilience of critical infrastructure systems. We next summarize these quantitative approaches, placing them into three broad categories.

2.1. Resilience-enhancing strategies (RES) prior to an extreme event

Several studies examine RES implemented prior to an extreme. This includes vulnerability studies and resource allocation models. Network vulnerability comprises examination of system resilience by identifying the element(s) most vulnerable to a disrupting event. This method is based on simulating both exogenous and endogenous shocks, relaxing the functionality of network element(s), and identifying those elements that impose the most risk to the system's effective operation. Sullivan et al. [43] investigated critical links in a regional transportation network using 335 traffic analysis zones (TAZs) and 1792 links. They studied an optimal capacity-disruption range to compare networks of different sizes and topologies. They showed that the rank-ordering of the most critical links varied with different capacity-disruption ranges.

Jenelius, Mattsson [13] analyzed the vulnerability of the Swedish road network under disruption covering area. They introduced a 'grid-based' approach – in contrast to the 'link-failure' method – covering the study area with grids of uniformly shaped and sized cells. They then simulated failures on cells consisting of both links and nodes, rather than just links. Murray-Tuite and Mahmassani [19] laid out a methodology for determining the vulnerable elements in an eight-link transportation network. Using a bi-level mathematical program, they modeled a non-zero-sum game with two players. In the first, a "bottom-up" model, the transportation management agency seeks the system's optimal traffic assignment. In the second, a "top-down" model, an "evil entity" maximizes network disruptions by targeting a set of links. Lou and Zhang [17] studied the reliability of travel time and unsatisfied travel demand using a tri-level game theory structure that included attackers, network users, and defenders. They modeled both random and targeted attacks on the Sioux Falls transportation network.

The second group – resource allocation models – investigates the allocation of resources/assets that provides the disrupted infrastructure with optimal functionality. This is achieved by pre-positioning resources on those elements having the most impact on a system's functionality if stressed or under attack [39,40]. It does so by considering all the possible events simultaneously. In multi-scenario models, the solutions aren't necessarily optimal against a particular event or aren't particularly addressing the most vulnerable element, as under network vulnerability studies. Beheshtian et al (2016) developed an asset allocation model, an extension to facility location problem, to locate g as stations optimum against maximum "functionality of the transportation network" over a course of disrupting scenarios.

In a series of studies, Rawls and Turnquist [35–37] modeled the impact of pre-positioning emergency resources. In their earliest study, they modeled an emergency response to hurricanes within a network of 30 nodes and 58 links in the southeastern United States. Using a bi-stage stochastic mixed-integer program, they examined the storage facility locations and sizes, as well as stocking decisions, for various types of supplies. In the second stage, they analyzed the distribution of available supplies in response to random events and network conditions. Rawls and Turnquist [36] next utilized stochastic mixed integer programming to minimize the expected costs of emergency supply pre-positioning considering the same network they studied in 2010. In their third study, Rawls and Turnquist [37] optimized the distribution of emergency supplies. They also extended their previous static models to include a dynamic approach where the evacuee arrival at shelter locations varies over time. To do so, they assumed cost minimization regarding the selection of pre-positioning locations and facility sizes, commodity acquisition, and their shipment.