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# An integrated network design and scheduling problem for network recovery and emergency response

Suzan Iloglu, Laura A. Albert*

*Department of Industrial Engineering & Systems Engineering, University of Wisconsin-Madison, 1513 University Avenue, Madison, WI 53706, United States*

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ABSTRACT

Effective recovery and restoration of infrastructure systems play a crucial role in recovery after disasters. This issue is particularly critical when delivering time-sensitive services and commodities. Damage to infrastructure can lead to disruptions and diminished capacity to respond to emergencies. We model the interdependencies between infrastructure systems and service providers as a network model, where emergency responders deliver critical services while network recovery crews repair damage to critical infrastructure. We present a novel extension to the P-median problem, where the objective is to minimize the cumulative weighted distance between the emergency responders and the calls for service over the time horizon by coordinating the activities of two types of service providers. We locate emergency responders (facilities) on a network over a finite time horizon while network recovery crews install arcs. The installation part of the models is modeled as a scheduling problem with identical parallel servers (the repair crews), where an arc can be used by the emergency responders when installation is completed. We propose Lagrangian relaxation formulations of the models, which we solve using subgradient optimization. A feasible solution is obtained using the Lagrangian relaxation, which provides an upper bound to the original models. We test our models with both real-world data and data sets from Beasley's OR Library to demonstrate the effectiveness of the algorithm in solving large-scale models. The results give insight into the optimal schedule for restoring critical arcs in a network when delivering critical services and commodities after a disruptive event.

## 1. Introduction

Emergency services play an integral role in responding to emergencies during and immediately after a disaster strikes to reduce both human suffering and property loss. At these times, delivering time-sensitive services and commodities is critically important for minimizing the risk to human life and health. For example, in 2012, Hurricane Sandy caused an estimated $65 billion in damage to the East Coast of the United States including damaging road and transportation infrastructure. The Tappan Zee Bridge, the Bayonne Bridge, the Hugh L. Carey Tunnel, and the Queens-Midtown Tunnel were all seriously damaged by Hurricane Sandy [1]. As a result of damage to these bridges and other transportation infrastructure, the affected regions experienced increased congestion and commute times that lasted for days after Hurricane Sandy [2]. The damage resulted in severe consequences. For example, a fire that occurred during the hurricane in Breezy Point, a neighborhood in the New York City borough of Queens, destroyed 126 houses. Serious damage to the roads made it difficult for responders to reach the houses in a timely manner, allowing the fire to spread and ultimately destroy more houses [3]. Also, Hurricane Sandy created 15 million cubic yards of debris due to the strong winds and heavy rains. The debris blocked roads, tunnels and transportation corridors in the effected areas and made the trips longer [4].

Damage to critical infrastructure can make the delivery of emergency services more difficult and increase response time during the recovery period. For example, in many disasters, damaged roads may have reduced capacity or may be impassable due to debris. Early stages of disaster recovery necessitate repairing this damage to critical infrastructure at the same time as critical services are delivered, thus aiding emergency response efforts. This paper studies how to coordinate these recovery efforts. We do so by introducing and analyzing integrated network design and scheduling models that determine how two types of service responders should work together to guide the restoration and recovery of infrastructure such as roads so that emergency services can be better delivered during the recovery period.

Few papers in the literature focus on interdependent infrastructure and network recovery to quantify the performance of the dependent infrastructures over a time horizon or planning period. However, there

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* Corresponding author.
*E-mail addresses:* iloglu@wisc.edu (S. Iloglu), laura@engr.wisc.edu (L.A. Albert).

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are some notable exceptions. Several papers formulate and solve network restoration problems in which infrastructure systems with critical system services are modeled as network flows [5]. Nurre et al. [6] introduce a new integrated network design and scheduling problem (INDS) that allows recovery crews to install nodes and arcs in the network to maximize the cumulative weighted flow through the network over a time horizon. This model can be used for short-term restoration and disaster preparedness activities. The installation components of our models have similar constraints to the model proposed by Nurre et al. [6].

Cavdaroglu et al. [7] propose an extension to INDS that also includes interdependencies between infrastructure systems. Instead of studying the performance of the system, the researchers focus on how quickly services are restored over the time horizon. Sharkey et al. [8] extend the interdependent layered network model of Lee et al. [5,9] to measure the performance of a system over the restoration period. They build upon the work of Cavdaroglu et al. [7] to consider damage scenarios that require restoration decisions for all infrastructure. Nurre and Sharkey [10] analyze 12 different INDS problems and show that all INDS problems are at least NP-hard. A related paper by Gutfraind et al. [11] introduces the neighbor-aided network installation problem as a discrete optimization problem to minimize the total cost of recovering a network. The authors propose a simple rule for recovering basic infrastructure networks by choosing the most accessible damaged network nodes in every iteration. Baxter et al. [12] introduce an incremental network design problem with shortest paths that focuses on network maintenance instead of network expansion in order to minimize the total cost over the planning grid. Likewise, Engel et al. [13] propose a theoretical framework to the incremental network design problem with minimum spanning trees. Duque et al. [14] introduce the Network Repair Crew Scheduling and Routing Problem (NRCSRP). They optimize the accessibility of demands by scheduling and routing a single recovery crew to repair roads starting from a single depot. Averbakh and Pereira [15] introduce the Flowtime Network Construction Problem (FNCP) and the weighted version of this problem (FNCP-W). They schedule the repairing of all unavailable vertices by a single recovery crew with the objective to minimize the total recovery time of the vertices.

We study network recovery in P-median model variations. Several other studies address related issues of recovery, reliability, and vulnerability in P-median models. Wang et al. [16] consider simultaneously opening new facilities and closing existing facilities with the objective of minimizing the total weighted travel distance for customers. They develop greedy interchange, Tabu search, and Lagrangian relaxation heuristics for the model. Reliability is a related issue in P-median models, where network damage is modeled as facilities that are sometimes unavailable for service. Snyder and Daskin [17] present location models that minimize cost, including the expected transportation cost of facility failure, with the goal of choosing facility locations that are concurrently reliable and inexpensive under traditional objective functions. They present reliability models for the P-median and uncapacitated fixed charge location problems, and they propose a Lagrangian relaxation algorithm to solve the models. Cui et al. [18] propose a reliability facility location design model that extends the work of Snyder and Daskin [17] to consider site-dependent failure probabilities as opposed to identical failure probabilities for all locations. O'Hanley et al. [19] study the unreliable *P*-median problem by considering site-dependent failure probabilities. They introduce a technique to linearize site-dependent failure probabilities of the facilities. A limitation of these papers is that they consider independent facility failures rather than cascading failures, which limits their applicability and do not address network restoration.

Another stream of papers relevant to disasters and large-scale emergencies studies vulnerability and protection strategies in location models [20,21]. Church et al. [22] introduce the *r*-interdiction median (RIM) problem and the *r*-interdiction covering (RIC) problem to identify the most critical facilities in the systems. These papers address the problem of identifying network protection strategies. The RIM model eliminates *r* facilities to maximize the cumulative weighted distance, and the RIC model maximizes the amount of demand no longer covered after *r* facilities are removed. Losada et al. [23] propose a bilevel mixed integer linear program to optimize resilience of the system against worst-case losses. They account for recovery time of facilities and multiple disruption probabilities over time in the model. Çelik et al. [24] consider the Stochastic Debris Clearance Problem (SDCP), which finds a sequence of roads to clear with the objective of maximizing satisfied relief demand. They model SDCP using partially observable Markov decision processes (POMDPs) that consider stochasticity in the debris (demand).

In this study, we make the following contributions:

1. We propose a new P-median problem variation that studies the interdependency between two types of service providers: network recovery crews who install arcs in the network and emergency response crews who are located at available facility locations where they deliver essential services. We schedule the installation of arcs over a finite time horizon by network recovery crews. Emergency responders can use these arcs once installation is complete to serve demand in demand points. The goal is to minimize the weighted cumulative distance between the emergency responders and the demand points over the time horizon. An extension to this model approximately models path-based arc installations between demand and facility locations. The proposed models are novel in that they coordinate the activities of two types of service providers, whose restoration activities are interdependent.
2. We introduce Lagrangian relaxation techniques to efficiently solve the models. We formulate and solve the Lagrangian relaxation dual problems using subgradient optimization, which yields a lower bound to the optimal objective function value. We propose heuristics to obtain a feasible solution to the models and an upper bound to the optimal objective function value using the Lagrangian relaxation.
3. We conduct extensive computational studies to demonstrate how these algorithms improve the time to solve the original models, and we discuss key insights gained from solving the models. The model solutions shed light on critical components of a network whose restoration can aid emergency response efforts.

The remainder of the paper is organized as follows. Section 2 provides the mathematical formulation of our models, applies the Lagrangian relaxation method to our models, and shows how to solve the relaxed models using subgradient optimization. It also provides a heuristic for finding feasible solutions to our models using the Lagrangian relaxation solution. Section 3 reports computational results and discusses the practical insights obtained from the results. The models and analysis shed light on the network components that should be prioritized during network recovery. Section 4 provides concluding remarks.

## 2. Model formulation

In this section, we introduce integrated network design and restoration models for recovering a network while providing emergency response services, and we formulate the models as integer programming models. The goal of the models is to coordinate the activities of two types of crews: emergency responders and repair crews. This is done by locating emergency responders and scheduling repair crews over a finite time horizon. At each time period, the models locate P emergency responders at open facilities in the network. The models also assign demand to open stations using available arcs in the network. This is accomplished using a multi-period P-median model, where locations are selected over time while allowing disrupted network components to