Working Title: Multi-Layer Infrastructure Repairs in a Post-Disaster Context

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Abstract

Keywords

1. Introduction

Hurricanes provide a growing concern in the operation of power grids in coastal areas. This paper was undertaken to address the gap in the literature where previous efforts don't consider how network layers depend on each other. To affect repairs on a damaged power grid element, the element must be accessible to the crew attempting to repair it, which implies that the road grid is a part of the repair efforts. In the process of a hurricane, the road grid will sustain substantial damage from flooding and debris on the road surface, which necessitates road grid repairs as well. To handle the issues of repairing power grids efficiently, consideration for repairs of both aspects should be considered jointly.

1.1 Existing Literature

Damage from hurricanes on infrastructure elements is well studied. All of [11], [10], and [6] have looked at the damage to power grids in varying capacities and methodologies. Damage to the road network is studied more in the context of repairing damage. [1] addresses concerns of accessibility to locations in the wake of road damage. [5] focuses their work on the ability to move disaster supplies around.

In the context of power grid repair, it comes from two major areas: Network interdiction and work similar to this paper. [9] is a paper emblematic of work on interdiction and provide the basis for the linear programming formulation of DC power flow used in this paper. [12] provides further literature review of the interdiction problem. [2] addresses a problem similar to this work, though without addressing travel times at all. [3] and [7] both address repairs to power grids in the context of resilience. Most similar to this paper is [4] in that they consider DC power flow and repair with travel times jointly. The key distinction is that they presume that the road operates under nominal conditions rather than including repair of the road grid into the problem.

2. Model

2.1 Overview

The problem to be addressed is how to handle interactions between road and power networks during disaster response. We choose to do this by solving the problems independently to keep runtime tractable and then testing a variety of post processing methods to handle the interactions. This should allow us to capture which interactions are worth the effort to address and which can be ignored in the name of preserving runtime or simplifying analysis

2.2 Assumptions

While considering coordinated repair using the mixed-integer programs below, we assume complete information about damage to both networks, complete information about repair times, and no variation in repair times. In the course of modeling the problem, we assume that a DC-flow model of power grid operation is close enough to real network behavior to draw useful insights [8]. We also assume in the power grid repair model that a minimum spanning tree can approximate routing elements NEEDS CITATION

2.3 Road Model

To model the road repair aspect of the problem, we choose to treat it as a problem of routing a crew tasked with clearing debris and flooding from roads. This is done by solving a variation of the prize collecting rural postman problem at each time step. The discrete time here is done to match up with both standard shift lengths and the discrete time requirement of the DC power flow based model for the power grid.

Defining Parameters and Sets to begin:

T	the set of time periods (shifts) over the time horizon
N	the set of nodes in the graph
C_{ij}	measure of the value of the road from i to j
L_{ij}	is the length of the road between nodes i and j when everything is working as normal
R_{ij}	time to repair the road between i and j
I_{ij}	initial condition of the road between i and j

2.4 Power Model

To model the power repair aspect of the problem, we treat it primarily as a scheduling problem. This repair schedule is subject to travel time and shift length constraints, which complicate things as well as an embedded DC power-flow model to evaluate each shift. NEED TO TALK ABOUT DISCRETE TIME ASSUMPTION?

We begin modeling the power half of the problem by defining the relevant parameters and sets

N	set of nodes, indexed by i
E	set of power lines, indexed by e
R	the set of road segments
T	the planning horizon, indexed by t
$O(i)$	set of lines with origin i
$D(i)$	set of lines with destination i
$o(e)$	origin node of line e
$d(e)$	destination node of line e
$\underline{L_e}, \overline{L_e}$	capacity lower and upper bounds for the power line e
Δ_i	time to repair node i
δ_e	time to repair line e
$C_{SP(i)}$	length of the shortest path to node i from the central depot
D_i	power demand at location i in the pre-disaster steady state
P_k	maximum power generation for generator k
B_e	line susceptance for power line e
I_e, I_i	initial condition of line e and node i, respectively

The model is then as follows

$$\min \sum_{i \in N} \sum_{t \in T} (1 - W_i^t) D_i \tag{1}$$

subject to:

$$X_e^t = B_e * (\theta_{o(e)}^t - \theta_{d(e)}^t), \ \forall t \in T, \ \forall e \in E \tag{2}$$

$$G_i^t - \sum_{l \in O(i)} X_l^t + \sum_{l \in D(i)} X_l^t = D_i, \ \forall t \in T, \ \forall i \in N \tag{3}$$

$$G_k^t \leq P_k V_k^t, \ \forall t \in T, \ \forall k \in N \tag{4}$$

$$\underline{L_e} W_e^t \leq X_e^t \leq \overline{L_e} W_e^t, \ \forall t \in T, \ \forall e \in E \tag{5}$$

$$\underline{L_e} V^t_{o(e)} \leq X^t_e \leq \overline{L_e} V^t_{o(e)}, \ \forall t \in T, \ \forall e \in E \tag{6}$$

$$\underline{L_e} V^t_{d(e)} \leq X^t_e \leq \overline{L_e} V^t_{d(e)}, \ \forall t \in T, \ \forall e \in E \tag{7}$$

$$MST^t = \sum_{i \in N} \sum_{j \in N} SP^t_{ij} * Z^t_{ij} C_{speed} \ \forall t \in T \tag{8}$$

$$\sum_{i \in N} \sum_{j \in N} Z^t_{ij} = \sum_{i \in N} F^t_i + \sum_{e \in E} S^t_e - \sum_{i \in N} F^t_i \sum_{O(i)} S^t_e - \sum_{i \in N} F^t_i \sum_{D(i)} S^t_e \ \forall t \in T \tag{9}$$

$$\sum_{i,j \in S} Z^t_{ij} \leq |S| - 1 \ S \subset N \tag{10}$$

$$\sum_{j \in N} Z^t_{ij} \leq F^t_i + \sum_{e \in O(i) \cup D(i)} S^t_e \ \forall t \in T \ \forall i \in N \tag{11}$$

$$\sum_{e \in E} \delta_e S^t_e + \sum_{i \in N} \Delta_i F^t_i + MST_t <= 8 \tag{12}$$

$$V^t_i \leq \sum_{t'=0}^{t-1} F^{t'}_i + I_i, \ \forall i \in N \tag{13}$$

$$W^t_e \leq \sum_{t'=0}^{t-1} S^{t'}_e + I_e, \ \forall e \in E \tag{14}$$

Constraints (2)-(7) define the flow on a damaged power grid with load being either switched on or switched off at a demand node. This is done to account for the last mile distribution lines being damaged at first making partial load shedding unrealistic.Constraints (8)-(11) handle construction of a minimum spanning tree between nodes being repaired during a shift to approximate the routing cost. We assume that a power line can be fixed starting from either of it's endpoints. Constraint (12) defines shift scheduling, and constraints (13) and (14) handle constraining operation to elements that are working.

3. Results

3.1 Methods

4. Conclusions

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