Two-Tier Fuel Distribution Planning for Disasters on Islands

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1. Introduction.

Fuel shortage is a critical issue on islands after disasters. People need gasoline for generators during power outages. After Hurricane Dorian, there was no power in the Bahamas' most hard-hit areas, and no fuel for generators. Traveling long distances for fuel slowed the response efforts (Fuel-Relief-Fund, 2019). Gasoline is used not only for power generators, but also for trucks delivering important supplies. ABC News reported that 10,000 shipping containers of potential relief bound for businesses were parked at the docks in San Juan after Hurricane Maria, but there was no gas or diesel for delivery trucks on the island (ABCNews, 2017). On islands, these shortages can particularly slow to resolve due to a lack of available refineries, damage to the transportation infrastructure, and time for additional fuel supplies to reach the island by sea or air.

To be prepared for disasters, islands need to have adequate fuel reserves. In preparation for the 2018 hurricane season, FEMA drastically increased its stockpiles (Flavelle, 2018). However, some hurricanes can have such big impacts on an island that ships must be brought in with additional fuel. For example, after Hurricane Maria (a category 5 storm), FEMA used barges to ship 100 fuel distribution trucks with 275,000 gallons of diesel and 75,000 gallons of gasoline to Puerto Rico (Hernndez, 2017).

In this paper, we propose a two-tier optimization approach to, first, determine how to allocate fuel to the different regions and the value of prepositioning additional fuel in the current and new locations (**Tier 1**). Second, for more severe events, we consider how to strategically use ships to supplement the prepositioned fuel (**Tier 2**). The contributions are that we study disaster response problems 1) that are particularly important on islands, 2) consider both equity and output in fuel distribution, 3) make decisions about fuel prepositioning based on a variety of scenarios derived from real disasters, and 4) evaluate the strategic use of ships to reduce service time.

2. Tier 1.

In **Tier 1**, we formulate a set of stochastic optimization models that focus on planning for equitable and efficient distribution of fuel after a natural disaster. In our models, we look at the delivery of

fuel from a set of reserve locations. Our stochastic models address the impact of potential disasters through the use of scenarios. In a scenario, we identify if existing fuel reserve locations are available or not and the fuel demands for each impacted region.

We present three models presenting different levels (**levels 1-3**) of flexibility in fuel distribution. For **Level 1**, we assume that the available fuel and resources for storing and distributing fuel are at *normal* levels seen before the disaster unless the reserve locations are affected by the disaster. In such scenarios, the affected reserve locations will be assumed to be unavailable. We optimize fuel distribution from the available reserve locations to regions to maximize both equity and output across the island. We define our first objective, equity, as the *smallest* fraction of the total fuel demand of any region on an island that is met by fuel deliveries as in (Li, Batta, and Kwon, 2017). This ensures all regions are treated fairly. We consider the total amount of fuel output as our second objective. This second objective is a good measure of effectiveness. This **Level 1** model helps identify how well demand could be satisfied with only the use of the existing resources.

We can potentially improve both the equity and output from our solutions to the **Level 1** formulation by storing extra fuel at one of the existing reserve locations or at a new location. We consider prepositioning both additional fuel reserves and additional delivery trucks at an existing fuel reserve location in our **Level 2** model. In **Level 3**, we want to find which region is best for building a new reserve to preposition extra fuel. If the improvements achieved by **Level 2** are not found to be satisfactory, we can evaluate if adding the extra fuel to an entirely new reserve location can be more effective.

We tested our models using scenarios based on real disasters in Puerto Rico. The results are shown in Figure 1. The average equity did not change by choosing from the existing locations. We

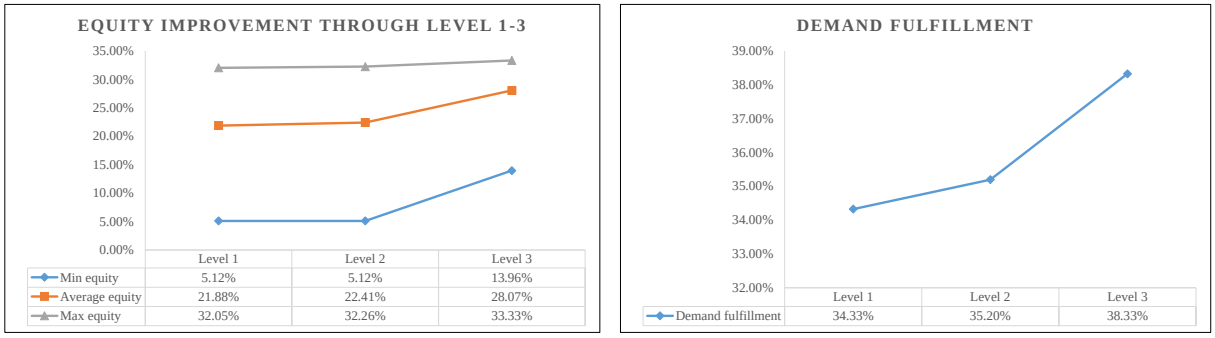


Figure 1 Tier 1 Results from GUROBI.

only get a real gain by considering an alternative low-risk location for fuel prepositioning and we get a considerable increase in the total output or demand fulfillment as well.

Our major insights are as follows: 1) the optimal prepositioning location is based on the amount of resources available and can vary for different parameter values, 2) we need a new location to get

a considerable impact, 3) using a mixed fleet of small and big trucks can provide slightly better equity and output levels than fleets consisting of only small or big trucks.

3. Tier 2.

In **Tier 2**, we examine the best strategies for using ships to supplement the fuel supply after a major disaster. We first consider a single ship and a set of ports $\mathcal{P}$. Ships travel across the water/between the ports, and tanker trucks travel on the island from the ports to fuel distribution centers. When a ship stops at a port, it incurs a fixed time before trucks can leave the port. Once the desired amount of fuel is unloaded into the port, the ship may leave the port. It can go to another port or return to the mainland. There is a set of fuel distribution points $\mathcal{F}$, and we initially assume the ship will serve all of the fuel distribution points. Once the fuel is unloaded into a port tank, trucks can start delivering to assigned fuel distribution points. We will assume that there are enough contracted trucks at each port that truck availability is not an issue. The variable z represents the latest time a truck arrives from any port to a fuel distribution point. The objective is to minimize z. The parameters, decision variables, and model are summarized below.

Parameters

d_{pf}: The travel time from port location p to distribution point f

s_{pl}: The travel time between ports p and l

u: The ship's fixed unloading time at a port

M: A big number

Decision Variables

n: The number of ports that a ship visits

z: The latest time a truck arrives at a fuel distribution point

x_{pl}: Equal to 1 if the ship visits port l after port p; 0 otherwise

y_{pf}: Equal to 1 if port p serves distribution point f; 0 otherwise

t_p: The time that the ship finishes unloading fuel at port p

$$\text{Min } z$$

$$\sum_{l\in\mathcal{P}:l\neq p} x_{pl} \leq 1 \qquad \forall p\in\mathcal{P}: p\neq 0 \tag{1}$$

$$\sum_{l\in\mathcal{P}\neq p} x_{lp} \leq 1 \qquad \forall p\in\mathcal{P}: p\neq 0 \tag{2}$$

$$\sum_{p\in\mathcal{P}} x_{0p} = 1 \tag{3}$$

$$\sum_{p\in\mathcal{P}} x_{p0} = 1 \tag{4}$$

$$\sum_{l\in P:l\neq p} x_{lp} = \sum_{l\in P:l\neq p\neq 0} x_{pl} \qquad \forall p\in\mathcal{P} \tag{5}$$

$$t_p \geq t_l + s_{lp} + u - M(1-x_{lp}) \qquad \forall l,p\in\mathcal{P}: p\neq 0 \tag{6}$$

$$z \geq t_p + d_{pf} - M(1-y_{pf}) \qquad \forall p\in\mathcal{P}, \forall f\in\mathcal{F} \tag{7}$$

$$y_{pf} \leq \sum_{l\in P} x_{lp} \qquad \forall p\in\mathcal{P}, \forall f\in\mathcal{F} \tag{8}$$

$$\sum_{p\in\mathcal{P}:p\neq 0} y_{pf} = 1 \qquad \forall f \in \mathcal{F} \tag{9}$$

$$x_{pl} \in \{0,1\} \qquad \forall p,l \in \mathcal{P} \tag{10}$$

$$y_{pf} \in \{0,1\} \qquad \forall p \in \mathcal{P}, \forall f \in \mathcal{F} \tag{11}$$

$$t_p \geq 0 \qquad \forall p \in \mathcal{P} \tag{12}$$

$$z \geq 0 \tag{13}$$

The objective function minimizes the latest time a truck arrives to any distribution point. Constraints (1)-(4) limit the travel of the ship to start and finish at the origin port, which is located on the mainland. Constraints (5) are connectivity constraints. Constraints (6) determine the time that the ship finishes unloading the fuel at a port, and Constraints (7) define z. Constraints (8) limit a port to serve a distribution point only if it is visited by the ship. Constraints (9) ensure that each distribution point is served by one port. Finally, Constraints (10) and (11) restrict x_{pl} and y_{pf} to zero or one, and Constraints (12) and (13) are the nonnegativity constraints.

For this model, we can identify structural properties such as:

Proposition 1 *With a makespan objective, it is optimal for a ship to stop at only one port if driving time is faster than ship travel time, and there is a complete network connecting the fuel distribution points to ports.*

We will also show solutions when the network is damaged, creating slower travel speeds, as well as when the network is not complete and disconnected.

References

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