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Modeling for Efficient Assignment of Multiple Distribution Centers for the Equitable and Effective Distribution of Donated Food

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Abstract

Food insecurity affects more than 41 million people annually in the United States. Within the Feeding America network, approximately 200 food banks are working throughout the US to serve people in need with donated food. Satisfying hunger need of food insecure people with limited supply is a challenge for these food banks. A numerical study is performed on data from Food Bank of Central and Eastern North Carolina (FBCENC) to capture the major attributes controlling its food distribution system. FBCENC seeks to distribute donated food equitably so that each service area (county) receives food proportional to its demand while minimizing the undistributed food donations. In addition to seeking equitable and effective food distribution policies, FBCENC wants to identify distribution branches to maximize the accessibility of the counties to donated food. An assignment and distribution model is developed to minimize the cost of maintaining a user-specified cap on the maximum inequity in food distribution. A sensitivity analysis between the user-specified maximum inequity cap and effectiveness shows the effectiveness of donated food distribution can be improved significantly by sacrificing equitable distribution slightly.

Keywords
Food distribution, food bank, equity, efficiency, effectiveness

1. Introduction

The United States Department of Agriculture (USDA) reports food insecurity as "a household-level economic and social condition of limited or uncertain access to adequate food." [1] According to USDA, 15.6 million (12.3%) U.S. households were food insecure at some point in 2016, including 41.2 million people of whom 13 million were children [2]. Within the network of Feeding America (FA), the largest national nonprofit hunger-relief organization in the U.S., 200 food banks are working to serve people in need with food donations. Through the network of these food banks, Feeding America receives and distributes donated food to people in need all over the United States. The food banks work as an autonomous body within their territory, though they report back to Feeding America with their monthly food distribution volume as well as the level of fairness in distributing that food. Feeding America imposes and regularly monitors a certain level of equity (proportion of demand fulfilled in each service area) to be maintained by these food banks while distributing the food donations. That equity requirement complicates the already complicated distribution system of a food bank.

In 2015, food insecurity in North Carolina ranked 6^{th} among U.S. states with 16.5% of the population (1,659,050 people) at hunger risk [3]. Food Bank of Central and Eastern North Carolina (FBCENC), a food bank within the FA network, serves food insecure people living in 34 counties of central and eastern North Carolina. FBCENC serves more than 630,000 people at hunger risk in these counties through a network of more than 800 partner agencies like soup kitchens, food pantries, shelters, and programs for children and adults[4]. As a nonprofit organization, the major objective for FBCENC is to distribute as much of the donated food as possible at the minimum cost while maintaining the required service level which is measured in terms of equity. In this article, we develop a mixed integer programming assignment and distribution model minimizing the total cost of shipping food donations from donor to recipient while maintaining a user-specified cap on maximum inequitable distribution and being effective by minimizing waste. We use data from FBCENC to perform sensitivity analysis between the maximum allowed inequity cap and effectiveness. These results demonstrate that slight sacrifice in equity can positively impact effectiveness and reduce cost.

The remainder of this paper is organized as follows. Section 2 addresses the relevant and recent studies that discuss donation distribution in emergency and long-term humanitarian relief efforts focusing on equity, effectiveness or efficiency. In Section 3, the details of the mathematical model are presented. Section 4 summarizes experimental results. In Section 5, research findings of this work and future research are discussed.

2. Related Literature

Several definitions of humanitarian logistics have been introduced in recent years. Apte [5] highlights the major challenges in this area and defines humanitarian logistics as a "special branch of logistics managing the response supply chain of critical supplies and services with challenges such as demand surges, uncertain supplies, critical time windows and the vast scope of its operations." Thomas and Mizushima [6] define humanitarian logistics as "the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from point of origin to point of consumption for the purpose of meeting the end beneficiary's requirements." In general, humanitarian logistics issues can be categorized into two types- disasters and long-term humanitarian development issues [7]. Although a significant portion of the literature on humanitarian logistics revolves around disaster management, the necessity and the impact of long-term humanitarian development is a significant challenge around the world.

Celik et al. [7] reviews the studies related to long-term humanitarian development and classifies the topics covered as food and supply distribution, infrastructure network planning in healthcare and supply chain optimization. The authors recognize lead-time, costs, equity, coverage, and distance to provider facilities as the major performance measures considered in those studies. In this paper, we focus on optimizing a food and supply distribution network in a humanitarian context with efficiency, effectiveness, and equity as the performance measures. Although the studies on disasters differ in periodic structure and problem constraints from the studies on long-term development issues, they often can have similar primary objectives or performance measures such as equity, efficiency, effectiveness. The definition of these terms though varies depending on the problem studied and the perspective of the decision makers.

Balcik et al. [8] define equity as maximizing the minimum fill rate (the ratio of allocated amount to observed demand) and minimizing waste as effectiveness. These authors propose a multi-vehicle sequential resource allocation problem that considers two critical objectives for nonprofit operations: providing equitable service and minimizing unused donations. Krejci [9] defines efficiency as fulfilling the demand for aid using minimal resources (i.e., money and time) while proposing a conceptual framework for a hybrid simulation model to determine how and whether certain coordination mechanisms enable better relief chain efficiency and effectiveness over time. Inspired by Orgut et al. [10] for the purpose of this paper, we define equity as equal distribution per demand, whereas effectiveness is used in the sense of utilizing the resource at maximum possible level. Unlike Orgut et al. [10], we include efficiency as a primary objective along with equity and effectiveness, where we define efficiency as "achieving an objective with lowest cost" [11].

Efficiency, equity, and effectiveness have been primary objectives for a good number of studies focusing on last mile relief distribution. Huang et al. [12] present an analysis in the last mile distribution problem focusing on efficacy (i.e, the extent to which the goals of quick and sufficient distribution are met) and equity (i.e, the extent to which all recipients receive comparable service). The authors analyze the impact of different objectives on route structures and the performance of aid distribution in terms of efficiency (transportation costs), efficacy and equity. Balcik et al. [13] propose a two-phase modeling approach to enable relief practitioners to make efficient and effective last mile distribution decisions. Ekici et al. [14] emphasize minimizing total cost while satisfying demand in their models for planning a food distribution network addressing facility location and resource allocation decisions during an influenza pandemic. While equity, effectiveness, and efficiency in distributing donations under a food bank supply chain network have been considered in different studies, to the best of our knowledge, no studies have combined these three attributes in a single study.

3. Model Formulation

3.1 Problem Statement and Assumptions

Though the primary goal of a food bank is to help as many people in need as possible, it also has to be fair to people in its service area while distributing the donations. FBCENC has the challenge to distribute food donations to people at hunger risk in each county within its territory within a desired maximum allowable level of inequitable distribution.

It also has to minimize the amount of undistributed food to be effective in distributing the donated food, which can contradict with the former objective. In addition, FBCENC wants to minimize the cost of collecting food donations from different sources and the cost of distributing those donations to different partner agencies working in different counties. All these goals and requirements are addressed by the mixed integer programming model presented in this paper.

FBCENC operates six branches in Durham, Greenville, New Bern, Raleigh, the Sandhills (Southern Pines) and Wilmington, which are the distribution centers in its supply chain network. Each branch is designed to send donations to partner agencies working in specific counties, which eventually distribute the donations to people with hunger need in its county. FBCENC receives donations from several sources: 59% of its total supply comes from the local donors, whereas 21% comes from state and federal government sources, 11% from FA and 9% from other food banks and food drives. Most of the FA and government donations come from Florida, which is considered as the hub in our model. In current practice, all the FA and government donations, and a portion of the local donations from different counties go to the Raleigh branch, which serves as the local hub for FBCENC. These foods are processed and stored at this location and then redistributed to different counties as required. In order to reduce the shipping cost, we propose to send the donations from the hub and local sources directly to the branch and then redistribute them among the partner agencies working in the counties served by that branch.

To ensure that all the major objectives and requirements of FBCENC are maintained we formulate a mixed integer programming assignment and distribution model that identifies the efficient allocation of counties to servicing branches and an equitable and effective food distribution policy. The following model assumptions are made.

- Agencies in a county are aggregated into a single agency and considered to be located at the centroid of a county.
- Each county receives food from only one branch.
- Trucks ship food to one location at each trip.
- Local supplies from a county go to the branch serving that county.

3.2 Notations and Formulation

The description of the index sets, parameters and variables used in the model developed are as follows. All the parameters and variables defined as demand, capacity or food distribution have pounds as the unit of measure, whereas costs are in dollars.

Index Sets and Parameters

I	Set of potential branches
J	Set of counties
o	Original hub for food supply
M	Set of existing branches
D_i	Demand in county i
C_i	Capacity of county i
κ_i	Capacity of branch i
c_{ij}	Cost of shipping a truckload of food to county j from branch i
ρ_{oi}	Cost of shipping a truckload of food to branch i from hub o
S	Amount of supply available from the hub
ξ_i	Amount of supply available locally at county i
c_w	Cost of discarding one pound of food as waste
c_f	Cost of operating a distribution center
c_p	Cost of processing food per unit
τ	Capacity of a truck
K	Maximum allowable deviation from equitable distribution

Decision Variables

f_i	$\begin{cases} 1, & \text{if county } i \text{ is selected as a branch} \\ 0, & \text{otherwise} \end{cases}$
Z_{ij}	$\begin{cases} 1, & \text{if county } j \text{ is assigned to branch } i \\ 0, & \text{otherwise} \end{cases}$
X_{oi}	Amount of food shipped from hub o to branch i
W	Total amount of wasted food
u_{ij}	Amount of food shipped to county j from branch i

Model

$$\text{minimize} \quad c_f \sum_{i\in I} f_i + \sum_{i\in I} \rho_{oi}\frac{X_{oi}}{\tau} + \sum_{i\in I}\sum_{j\in J} c_{ij} Z_{ij}\frac{\xi_j}{\tau} + \sum_{i\in I}\sum_{j\in J} c_{ij}\frac{u_{ij}}{\tau} + c_p * \sum_{i\in I}\sum_{j\in J} u_{ij} + (c_w + c_p)W \tag{1}$$

$$\text{subject to:} \quad \sum_{i\in M} f_i = ||M|| \tag{2}$$

$$\sum_{i\in I} Z_{ij} = 1, \qquad \forall j \in J \tag{3}$$

$$X_{oi} + \sum_{j\in J} Z_{ij}\xi_j \leq \kappa_i * f_i, \qquad \forall i \in I \tag{4}$$

$$\sum_{i\in I} X_{oi} \leq S \tag{5}$$

$$\frac{\sum_{i\in I} u_{il}}{D_l} - \frac{\sum_{i\in I} u_{ik}}{D_k} \leq K, \qquad \forall l \in J, k \in J, l < k \tag{6}$$

$$\frac{\sum_{i\in I} u_{ik}}{D_k} - \frac{\sum_{i\in I} u_{il}}{D_l} \leq K, \qquad \forall l \in J, k \in J, l < k \tag{7}$$

$$W = S + \sum_{j\in J}\xi_j - \sum_{i\in I}\sum_{j\in J} u_{ij} \tag{8}$$

$$\sum_{j\in J} u_{ij} \leq X_{oi} + \sum_{j\in J} Z_{ij}\xi_j, \qquad \forall i \in I \tag{9}$$

$$u_{ij} \leq Z_{ij} C_j, \qquad \forall i \in I, j \in J \tag{10}$$

$$u_{ij} \leq D_j f_i, \qquad \forall i \in I, j \in J \tag{11}$$

$$f_i, Z_{ij} \in \{0, 1\}, \qquad \forall i \in I, j \in J \tag{12}$$

$$X_{oi}, u_{ij}, W \geq 0, \qquad \forall i \in I, j \in J \tag{13}$$

The objective function (1) minimizes the sum of the cost of maintaining branches, the cost of shipping donations from sources, the cost of distributing donations to agencies, the cost of processing donated food and the cost of food wasted. Constraint (2) ensures the continuation of the existing branches. Constraints (3) restrict each county to be served from only one branch. Constraints (4) assert that each branch receives donations within its capacity. Constraint (5) ensures that total donations shipped from the hub to all the branches are no greater than the donations available at the hub. Constraints (6) & (7) put a cap on the absolute difference of the proportion of demands fulfilled between any two counties. Constraint (8) defines any undistributed food as waste. Constraints (9) ensure total distribution from a branch is less than the donations received by that branch. Constraints (10) and (11) ensure that food shipped to a county is below its capacity and demand, respectively. And finally, constraints (12) and (13) impose the binary and non-negativity restrictions on f_i, Z_{ij} and X_{oi}, u_{ij}, and W, respectively.

4. Computational Results

4.1 Experimental Settings

We run our model with data from FBCENC to observe its performance. FBCENC receives donations broadly of four categories: dry goods, produce, refrigerated food, and frozen food. In this paper, we focus on dry goods which were about 58% of FBCENC's total distribution of donated foods in 2016, the highest by far. The actual distribution of dry goods in October 2016 by FBCENC defines the total supply of which 59% comes from local sources and the rest are considered to be from the original hub. For simplicity in the shipping cost calculation, we do not consider the actual location of the 9% of donations coming from other food banks and food drives. The 90^{th} percentile of the empirical distribution of the amount of food shipped to a county each month during the fiscal year 2016 is used as an estimate of each county's capacity [10]. Despite the fact that demand data is difficult to predict as the food insecure population of a county may change over the time period considered, it is reasonable to consider demand proportional to the estimated poverty population in the counties. We use the Feeding America "Map the Meal program" to convert the demand in population into demand in pounds of food[15].

The shipping cost is calculated by multiplying the centroidal distance between origin and destination by an estimated fuel cost per mile and the number of truckloads is obtained from dividing the total food distribution to the destination county by the truck capacity. The other cost components like the branch operating cost, food processing cost and cost of undistributed food were acquired from FBCENC. In the model, we divide the shipping costs into elements as the food donations come to FBCENC from different sources, and are redistributed to different counties. The model is programmed using IBM ILOG Optimization Programming Language and solved using CPLEX as the underlying MIP solver.

4.2 Results

We ran the model for different equity scenarios to study the impact of equity on effectiveness and efficiency. Under perfect equity (K=0), the optimal solution has the highest total cost with food waste contributing significantly to the total cost. In this case, the counties become capacity-constrained by the county with the lowest capacity to demand ratio, and no counties can receive more than that county should receive. As a result, a good amount of donations remains undistributed. This situation can be improved significantly with a marginal sacrifice in equity making the system more effective and efficient. Figure 1(a) shows that the total cost is initially driven by the wastage cost, but after a certain level of deviation (K=0.06) from perfect equity, the total cost is equal to the transportation cost, food processing and other operating cost, as the wastage cost becomes zero after this point.

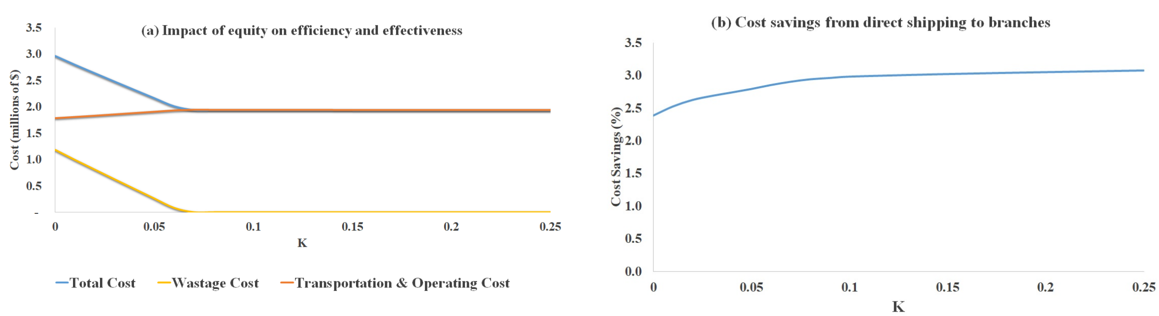

Figure 1: Impact of equity and proposed change in the network on cost

In addition, our proposed model suggests it is cost effective to ship food donations directly to each of the six branches instead of shipping donations to the Raleigh branch, which works as a local hub in the current practice, to process the foods and redistribute. A comparison between these two model networks shows that our proposed network saves around 2.38% to 3.08% of the total cost for a range of K = 0.0 to 0.25, over the existing practice by reducing the shipping cost (Figure 1(b)).

5. Conclusions and Future Work

In this paper, we develop an assignment and distribution model to determine the optimal allocation of food donations to different counties served by FBCENC. As per the FA guidance, FBCENC seeks to maintain equitable distribution while distributing the available donations as efficiently as possible. Perfectly equitable distribution is the most costly solution as it may result in a large amount of waste. A slight deviation from perfect equity can significantly reduce food waste eventually reducing the total cost of the system. Moreover, changing the current practice of sending all supplies to a single hub for processing to sending supplies to the local branches reduces the total shipping cost of the system.

The model can be used to solve similar problems for other types of food, e.g., produce, frozen goods, etc. We are extending this model to incorporate the stochastic nature of food supply and capacity of different counties within the FBCENC service area. One limitation of the model, we may underestimate the transportation cost by underestimating the number of truckloads needed to ship food. In addition, a new step will be to incorporate the cost of enhancing the food processing capacity of other branches in order to better assess the savings of the proposed network.

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