Modeling for Equitable and Effective Food Distribution in North Carolina

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Abstract

The Food Bank of Central and Eastern North Carolina distributes food to a 34-county service area. The objective of this research is to determine the equitable and effective distribution of donated food among people at risk for hunger. In this context, supply is donated; demand typically exceeds supply and is proportional to the poverty population. Equitable food distribution allows each individual in the considered community to have equal access to the donated food such that no individual is at a disadvantage compared to others. We define effectiveness as the ability to distribute as much food as possible from the donated supply, which often conflicts with the objective of equity. Factors that influence the solution of this problem are capacity, demand and supply. We develop deterministic, capacity-constrained network flow models maximizing effectiveness while maintaining equity. We then study the effect of distribution capacities on the optimal food distribution policy.

Keywords
Operations research, equitable food distribution, humanitarian logistics, capacitated network flow problems, mathematical linear models.

1. Introduction
According to the Food and Agriculture Organization of the United Nations [1] about 870 million people in the world suffered from food insufficiency and hunger in the period 2010 – 2012. In 2011, 50.1 million Americans lived in food insecure households; 33.5 million adults and 16.7 million children [2] and these statistics are climbing each year. Food insecurity is defined as “a household-level economic and social condition of limited or uncertain access to adequate food” and hunger as “an individual-level physiological condition that may result from food insecurity” by the United States Department of Agriculture [3]. Although the term “hunger” was more common in the 1980s, “food security or insecurity” is the term commonly used today.[4] This paper analyzes the operations of a large food bank located in North Carolina to identify equitable and effective distribution strategies for donated food to the population in need.
The Food Bank of Central and Eastern North Carolina (FBCENC), located in Raleigh, NC, distributes food and other donations through its warehouse and four branches (located in Wilmington, Durham, Sandhills, and Greenville, NC) to partner agencies such as food pantries and soup kitchens in a 34-county service area. The food is distributed to the needy population in the counties by these partner agencies. Each branch is assigned a set of counties to serve, and a county may receive food from more than one branch. Food can be transferred from one branch to another before the distribution to agencies. FBCENC’s food distribution supply chain is illustrated in Figure 1.

Capacity issues in this supply chain can be studied at several different levels. The flows of donated food through this supply chain network are constrained by capacities at individual FBCENC branches and counties, as well as the transportation resources available to distribute the food. Branch and county capacities arise due to limited storage space, as well as budget restrictions at individual agencies constraining their ability to purchase food. In this study, our focus is on the capacities at county levels.

A fair-share formula, which defines the demand for donated food based on the estimated population in poverty (as defined by the Federal government) in each county is used by FBCENC for the distribution of food donations. FBCENC is required to distribute food across counties in proportion to the population in poverty in each county so that, ideally, each person in poverty in FBCENC’s service area would receive exactly the same amount of donated food by weight over a specified reporting period. However, historic distribution data suggests that some counties are at a disadvantage compared to others in terms of obtaining their share of the donated food. Specifically, the food donations received per person in one county may be less than those received by people in another county. In this study, we develop mathematical models to maximize the amount of distributed food while maintaining equity as defined by the fair share measure. The models can be used both for benchmarking the performance of FBCENC by exploring the tradeoff between equity and the total distributed tonnage, and for obtaining managerial insights regarding how capacity investments can be made in collaboration with local agencies to improve the ability of FBCENC to meet its goals.

Figure 1: Food Bank of Central and Eastern North Carolina Supply Chain
In the next section, we briefly review the related literature on food distribution and the definition, measures and applications of equity in various areas. In Section 3, the linear models are presented. Section 4 includes the methodology and data acquisition for this study. We then present some results that support the claims obtained from the models and the major conclusions from this study. The paper concludes with a discussion of the limitations of the current work and directions for future research.

2. Background & Literature Review

In this research, we apply operations research tools to determine the equitable and effective distribution of food donations among people in need. There are various studies in the food distribution literature that focus on problems related to the relief of food insecurity. Hwang [5] focuses on developing a distribution model to determine the optimal allocation of food and inventory in a famine relief area by using an integrated approach of inventory allocation and vehicle routing problems. He performs a case study in a North Korean region experiencing famine. Adivar et al. [6] define a “Social Welfare Chain” as “the processes of designing, planning and implementing a wide range of social development and improvement programs involving all the logistics activities in meeting the needs, managing social problems and maximizing the opportunities for the purpose of improved social welfare”. This definition is also appropriate for the supply chain in our problem. They point out that social welfare and humanitarian relief chains have similarities in terms of their reasons for existence but they are different due to the structures of the supply chains. Also, social welfare chains differ from commercial supply chains in that they have donors and government as suppliers and beneficiaries as recipients. The authors point out that operations research has been widely used for sudden-onset disaster relief operations but “very little, if any, research focuses on optimizing relief efforts for slow-onset disasters or social welfare operations”. They formulate a linear mixed integer programming model with the objective of minimizing total cost for coal distribution in Turkey with various constraints. Schweigman et al. [7] also utilize operations research tools to overcome food insecurity in developing countries by focusing on obtaining the optimal level of land that should be cultivated to ensure that no food shortage occurs. Rong et al. [8] point out the difficulties in dealing with a food supply chain due to food – specific characteristics that are different from traditional commodities and note that the studies of food supply chains are limited. Although there are some studies that focus on food distribution in a non-profit food chain, to our knowledge, there are no studies that consider food distribution with the objective of satisfying equity.

Since the notions of equity and fairness form the core of our study, it is important to examine the corresponding literature on defining and applying those notions. Sen [9] states that economic inequality can be described either in an objective sense (using some statistical measures) or in terms of some normative notion, i.e. a higher degree of inequality corresponds to a lower level of social welfare for a given total of income. In this research we use the maximum absolute deviation as a measure of inequality. Since fairness and equity are abstract socio-political and subjective concepts, it is not possible to determine an equity measure that is applicable to all different types of problems [10].

There has been a wide range of applications in the literature considering equity and the equitable allocation of different types of resources. Marsh et al. [11] give a brief overview of the many areas where equity is used as an objective. Some examples of these areas are geographers’ concerns regarding equitable distribution of water rights in Western states, political scientists’ discussions on each state having equal representation in Congress and economists’ studies on public welfare distribution and equitable distribution of income. Furthermore, they focus on facility siting decisions and they state that equity is obtained if each group that is affected by the facility siting decision receives their fair share from the total effect. Their objective is to minimize inequity by using 20 different measures proposed in literature and compare and analyze them for different situations. Meng et al. [12] formulate the Continuous Network Design Problem which is basically the problem of allocating a capacity increase among existing roads under a budget constraint. They use a bilevel programming approach and incorporate equity as a constraint where different network users receive equal benefit from the capacity increase in terms of their average origin – destination travel costs.

Another area where equitable distribution of resources is important is the allocation of emergency medical resources. Chanta et al. [13] consider the problem of determining locations of facilities to locate ambulances such that the total “envy” over all the demand zones is minimized. Their definition of envy is based on the patient’s dissatisfaction due to his distance to nearby ambulance facility locations; hence their approach is similar to minimizing total inequity. They formulate the problem as an integer programming model called the minimum $p$-Envy Location Model.
In their study, Vossen et al. [14] also focus on an interesting equity problem. Their objective is to allocate the national air space equitably such that the amount of possible delay is distributed equitably among flights. They propose that the ration-by-schedule approach gives nearly equitable allocation of resources and minimizes total delay. Mazumdar et al. [15] study a multiuser telecommunications network in which each user has the objective of optimizing its performance while being fair to the other users. They propose that the Nash arbitration scheme from Game Theory gives a desirable and fair solution for individual users and different performance criteria. The solution obtained from this method is Pareto optimal. Finally, Ogryczak [10] addresses the tradeoff between equity and effectiveness in resource allocation models. He explains different performance measures to achieve Pareto optimality of a solution since this solution is also efficient and states that the max-min types of objectives give both equitable and effective solutions and can be used in some applications. As seen above, there have been many studies with the objective of satisfying equity over some measure. However, to the best of our knowledge, determining the optimal allocation of food in a donations-based supply chain remains undiscovered despite its theoretical and social interest.

In this study, we formulate network flow problems with capacity constraints and allocate donated food to maximize the total amount of food that is distributed with minimum deviation from a completely equitable distribution. Although, according to our knowledge, there is no study based on donated food supply chain with capacity constraints, the general ideas and methods from production supply chains provide useful insight about our problem. Toktay and Uzsoy [16] investigate a machine capacity allocation problem in a semiconductor wafer fabrication facility to maximize throughput and minimize deviation from predetermined production goals. The authors show that these two objectives are actually equivalent and both strongly NP hard and develop heuristics to find near optimal solutions. Ulusoy and Uzsoy [17] work on the strategic mobility problem which is defined as “the problem of moving a known amount of resources from a number of supply points to a number of demand points using a number of vehicles.” As a special case, they consider the airlift problem and their purpose is to locate supplies and aircrafts to minimize the maximum operating time while considering possible demand patterns. They consider two levels of planning: first is the allocation of supplies and the second is identifying the optimal action for routing the aircraft in a particular situation. For the first level they use a mathematical model with a scenario approach and for the second level they use a heuristic approach. This two-level planning system for allocating resources could also be applied to our model in the future since the distribution occurs at both the branches and the counties. Finally, Parlar and Perry [18] consider the inventory planning problem in a production facility under supply uncertainty. They model this as a continuous-time Markov chain where the states are associated with the supplier availability. They consider a single machine problem with a single supplier, two suppliers and multiple suppliers. Although aspects of our problem are stochastic in nature, in this paper, we focus on the deterministic, capacity constrained equitable allocation problem.

3. Models for Equitable and Effective Food Distribution
We present a series of linear programming models to obtain the optimal allocation of donated food considering both equity and effectiveness. To obtain insight, we first develop a model based on aggregated total tonnage of a single food group such as dry goods. Distribution is said to be equitable if each person in poverty in the considered service region receives the same amount of distributed food. On the other hand, the distribution is effective if the maximum amount of supply gets distributed, considering all constraints. Demand is considered to occur at the county level, hence the agencies in a given county are aggregated to provide estimates of the distribution capacity in that county, i.e., the total tonnage of food that the county can receive and distribute with minimal wastage. Here, it should be emphasized that the purpose of our models is not to satisfy demand since the total supply is always much lower than the demand. For example, if we look at the actual food donations during January – June 2009, and divide that value by the estimated poverty population in the service region during that time (obtained from U.S. Census Bureau data [19]), we find that on average the donations are 3.5 pounds of food per person per month. This very low poundage highlight the fact that satisfying demand can never be an objective in this system; rather, the approach taken is to distribute the donations in an equitable way while minimizing waste where demand is representative of the proportion of total poverty population located in a given county in relation to the other counties.

Although the actual supply chain consists of five warehouses where food donations are collected, we will aggregate the donations of these five warehouses into a single supply node since transfers between warehouses are allowed in the real system and transportation cost is not considered in our models. It can be shown that this is not a constraining assumption since food can be transferred among branches with no cost and hence they can be treated as a single,
aggregated branch. Our models consider the allocation decisions that the Food Bank faces in a single time period, such as a month. This represents the common practice of the Food Bank since they usually choose to distribute their food supply to their agencies as soon as possible. We propose the following model:

**Model 1:**

\[
\min P
\]

\[
\sum_{k=1}^{n} \frac{X_j}{X_k} - \frac{D_j}{\sum_{k=1}^{n} D_k} = 0 \quad j = 1, \ldots, n
\]  

\[
S - \sum_{k=1}^{n} X_k - P = 0
\]  

\[
X_j \leq C_j \quad j = 1, \ldots, n
\]  

\[
X_j, P \geq 0 \quad j = 1, \ldots, n
\]  

In this model, the decision variable \(X_j\) represents the total pounds of food shipped from all warehouses to county \(j\), \(j=1,\ldots,n\). \(P\) represents the amount of supply that remains undistributed. \(D_j\) denotes the demand observed at county \(j\). \(S\) is the amount of food donated to the single branch (aggregated over five branches). \(C_j\) represents the receiving capacity of county \(j\) (aggregated over the agencies located in that county). All parameters are in units of pounds.

Constraint (1) enforces the equitable distribution of food by ensuring that each person in the considered service region receives the same amount of food; this is accomplished by setting each county’s share of the total food distributed equal to their relative percentage of demand over all counties. Constraints (2) enforce conservation of flow at the branch level. Constraint set (3) represent the capacity constraints for each county \(j\). Constraints (4) are non-negativity constraints. The objective function minimizes the total undistributed supply. The nonlinear Constraint (1) can be approximated by rewriting it as the following.

\[
X_j \sum_{k=1}^{n} D_k - D_j \sum_{k=1}^{n} X_k = 0 \quad j = 1, \ldots, n
\]

This model assumes that all demand, supply and capacity parameters are deterministic. The estimation of these parameters is a complex task in itself, which we shall address in the Methodology section. Proposition 1 identifies the optimal solution to this model and introduces an important definition.

**Proposition 1:** In an optimal solution to Model (1), the counties with the smallest capacity over demand ratio (defined as the bottleneck counties) will receive an amount of food equal to their capacities whereas the remaining counties will receive less food than their capacities. Furthermore, if we define

\[
R_1 = \min\{C_j / D_j : j = 1, \ldots, n\}
\]

the optimal solution to Model (1) is given by

\[
X'_j = \min\{R_1 D_j, S \sum_{k=1}^{n} D_k / D_k\} \quad j = 1, \ldots, n
\]

and,

\[
P' = \max \left\{S - R_1 \sum_{k=1}^{n} D_k, 0\right\}
\]

Proposition 1 highlights that the optimal solution is constrained by either the bottleneck counties’ capacities or the total supply. If the constraining factor is the capacity, in the optimal solution to Model (1), the bottleneck counties will receive food equal to their capacities, hence utilizing their capacities completely. The remaining counties, however, will end up with idle capacity. Therefore, the optimal level of equity and effectiveness is directly affected by the minimum capacity to demand ratios among the counties. These results imply that the amount of food distributed cannot be increased while maintaining equity unless the capacities of the bottleneck counties are increased (since demand is an exogenous parameter and cannot be changed). On the other hand, if the constraining factor is supply, then the supply is distributed among the counties according to their proportion of total demand so that each person receives the same amount of food. The proof of this proposition is based on the constraints of the model.
A problem of interest to the Food Bank is the allocation of additional capacity to the counties such that equity is maintained and effectiveness is increased. This type of model also allows the Food Bank to determine the amount of capacity needed to obtain a desired improvement in effectiveness, or the amount of additional delivery that can be obtained with a given amount of additional capacity. This type of situation arises when the Food Bank obtains funding to purchase $Y$ units of extra capacity, such as refrigerated units, for distribution among the agencies in the different counties, to enable the agencies to distribute more food in their areas. Our models do not consider the cost associated with the allocation of additional capacity to the counties as our focus is to identify priorities for the allocation of additional capacity. The Food Bank can use this information to identify external funding sources. Therefore, the problem is to determine the optimal way to allocate this capacity in order to increase level of distribution effectiveness in relation to Model 1. This problem can be formulated as follows:

**Model 2:**

$$\text{max } Q$$

$$Q \leq \frac{C_j + \rho_j Y}{D_j} \quad j = 1, \ldots, n$$

$$\sum_{k=1}^{n} \rho_k \leq 1$$

$$Q, \rho_j \geq 0 \quad j = 1, \ldots, n$$

The only new parameter is $Y$ which represents the amount of extra capacity available for allocation in pounds of food. The decision variable $\rho_j$ represents the percentage of the additional capacity $Y$ to be allocated to county $j$. $Q$ represents the minimum capacity to demand (CD) ratio of the counties after the additional capacity is allocated. Constraints (9) combined with the objective function indicates that the objective of this model is to maximize the minimum capacity to demand ratio (CD ratio) among the counties. Constraint (10) indicates that the total amount of capacity distributed cannot exceed the additional capacity on hand, $Y$. Constraints (11) are non-negativity constraints.

We propose an efficient algorithm to solve Model (2) exactly. The detailed statement of this algorithm is not given here but the general outline can be explained as follows. The algorithm works in an iterative fashion. There are at most $n$ iterations, each of which examine the set of bottleneck counties and try to increase their CD ratio to the level of the next lowest CD ratio at that iteration. At each iteration, the minimum CD ratio, the set of bottleneck counties and the second lowest CD ratio are calculated. Next the additional capacity required to increase the minimum CD ratio to the level of the next lowest CD ratio is obtained. If there is enough remaining capacity to perform this action, the capacities of the bottleneck counties are increased so that their CD ratio equals the next lowest CD ratio. Otherwise all remaining capacity is distributed among the bottleneck counties such that their CD ratios remain equal to each other and the algorithm is terminated. If we reach iteration $n$, i.e. all CD ratios are equal, all remaining capacity is distributed among the counties such that their CD ratios remain equal to each other and the algorithm is terminated. The following proposition which identifies the optimal solution to Model 2 is derived from the capacity allocation algorithm and hence is given without proof.

**Proposition 2:** In the optimal solution to Model (2), there will be $m$ bottleneck counties where $m$ is determined such that:

$$\sum_{k=1}^{m-1} \left( \frac{C_m}{D_m} D_k - C_k \right) \leq Y < \sum_{k=1}^{m} \left( \frac{C_{m+1}}{D_{m+1}} D_k - C_k \right)$$

and $m \leq n$.

The optimal solution is given by

$$Q = \frac{Y + \sum_{k=1}^{m} C_k}{\sum_{j=1}^{m} D_k}$$

$$\rho_j = \frac{Q D_j - C_j}{Y} \quad \text{for } 1 \leq j \leq m$$

$$\rho_j = 0 \quad \text{for } m + 1 \leq j \leq n$$
Proposition 2 provides a closed form solution to the capacity allocation model. The proportion of extra capacity that a county receives is directly proportional to the county’s demand and inversely proportional to its capacity so that more densely populated areas receive more capacity, as expected. The additional capacity on hand, \( Y \), is a known parameter in this formulation and by using the results from Proposition 2, combined with Proposition 1, we can calculate the increase in the distribution effectiveness (total tonnage of food distributed) directly. An example of this will be shown in the Results section.

4. Methodology
FBCENC classifies the donated goods into four categories: dry goods, produce, refrigerated food and frozen food. This study focuses on a single food category; the interactions and capacity substitutions between different food groups will be considered in future work. In this section we illustrate the behavior of the models in Section 3 considering dry goods category. The actual donations made to FBCENC’s five branches during January 2009 constitute the supply data and since our models assume a single supply node, this data is aggregated. In this problem, it is not possible to predict demand with certainty although it is reasonable to assume that demand is proportional to the poverty population in the county. However, the definition of the poverty population is itself somewhat arbitrary, since families and individuals enter and leave this population constantly for a variety of reasons such as relocation, job loss or new employment. It is important to note that satisfying demand is not possible since it significantly exceeds supply. Hence, satisfying demand is not the objective in this formulation. Instead, we determine the fair amount of donated food to be sent to a county based on its poverty population. The poverty populations for the counties are obtained from U.S. Census Bureau data [19]. In order to estimate the capacity of a county, the actual amount of food shipped to that county during fiscal year 2009 is used. The 90th percentile of this empirical distribution data is used to represent that county’s capacity. This is a reasonable estimation since it gives an idea of what that county can absorb in general. These assumptions have also been validated with FBCENC.

5. Results
The proposed models are solved using Optimization Programming Language (OPL) [20]. Initially Model (1) is solved with the data described above. Model (1) requires that every person in poverty living in the considered service region must receive the same amount of donated food, and the amounts distributed depend on the receiving capacities of the agencies. Figure 2 illustrates the results from Model (1) and supports Proposition 1. In Figure 2, the horizontal axis shows the 34 counties in the considered service region in increasing order of their capacity to demand ratios. The dark grey line shows the ratios of the flows received by the counties to their capacities; these values are given on the primary vertical axis. The bars represent the capacity to demand ratios of the counties and their values are given on the secondary vertical axis.

![Results from Model (1)](image)

Figure 2: Distribution Allocation Solution from Model 1 to Capacity ratio by county according to increasing CD ratio
Figure 2 provides some important insights into the structure of our problem as predicted by our analysis. First, it shows that the calculated ratio of flows received by counties over their capacities is equal to one for Wilson County and less than one for the remaining counties. This means that Wilson County receives the amount of food equal to its capacity, while the remaining counties receive less than their capacities. Thus, Wilson County is the bottleneck county with the smallest capacity over demand ratio and receives an amount of food equal to its capacity. Here, the constraining parameters are the capacities of the counties, not supply. The remaining counties receive less food than their capacity and hence are penalized by the enforcement of equitable distribution across counties with different capacities.

We also examine the problem of allocating additional capacity to the counties in Section 3. We observe that the solution to this problem has a step-wise nature where at each step we increment the number of bottleneck counties by one (assuming that none of the capacity over demand ratios are equal to one another). We illustrate the results from Model (2) in Figure (3).

![Figure 3: Minimum Extra Capacity requirements as identified by Model 2 and potential Supply Distribution by county according to increasing CD ratio](image)

In the horizontal axis in Figure 3 the counties are presented in increasing CD ratio order. The dark grey bars represent the minimum amount of extra capacity needed to add the corresponding county to the set of bottleneck counties. It is important to note that this follows a cumulative addition fashion such that; for example if there are 500,000 pounds of additional capacity to be allocated, the bottleneck counties become: Wilson, Granville, Wayne, Sampson, Onslow, Halifax, Orange, Lenoir, Wake, Craven, Warren, Carteret, Pitt, Johnston, Durham, New Hanover, Person, Greene, Nash and Columbus. Franklin County cannot be added to the list because 559,986 pounds of additional capacity would be required to include Franklin County, as can be seen from the graph. The light grey bars show the amount of food that can potentially be distributed when additional capacities are allocated. As the number of bottleneck counties and their capacities increase, distribution effectiveness increases while equitable distribution is maintained. Finally, the horizontal line represents the supply (actual food donations made to the Food Bank during the considered time period). Even if the capacities are increased, at some point, the distributions start to be constrained by the supply rather than the capacities. This analysis provides a useful measure for FBCENC to see how their distribution effectiveness (total tonnage of food distributed while maintaining equity) can increase as a result of extra capacity and supply; they can directly see how they could benefit from increasing their capacities and supply levels.

Next, we consider the case where there is an additional 2,500,000 pounds of capacity available for distribution to the counties. Figure 4 illustrates the optimal distribution of this additional capacity to the counties in the service region.
Figure 4: Optimal allocation of extra 2,500,000 pounds of capacity to the counties

All counties are included in this pie chart since each county receives additional capacity in the optimal solution. As shown in Figure 3, 2,500,000 pounds of extra capacity is enough to make all 34 counties bottleneck counties. We notice that Wake and Durham counties obtain the largest proportion of this extra capacity since these are densely populated counties with relatively low capacity.

6. Conclusions

In this study, we develop models to determine the equitable and effective distribution of food donations. The conflicting objectives of equity and effectiveness play an important role in this formulation where we define effectiveness as the ability to distribute as much food as possible to the counties in the service region. On the other hand, a distribution is equitable if no person at the community is at a disadvantage in terms of receiving donated food. First, we formulate a linear programming model that enforces equitable distribution and maximizes effectiveness. We show that either the supply or the capacities of the counties determine the closed form optimal solution. If there is enough supply, the counties with the smallest capacity to demand ratio (the bottleneck counties) are important in terms of determining the optimal distribution. In order to increase effectiveness, we have to increase the capacity of the bottleneck counties. This idea leads to our second model where we examine the case that the Food Bank has extra capacity to allocate to the counties. We prove that a stepwise capacity allocation algorithm gives the optimal distribution structure for extra capacity. As a case study, we use the data obtained from FBCENC to illustrate these findings.

An important conclusion from this study is the notion of the bottleneck county and how it affects the allocation decisions in terms of the equity-effectiveness tradeoff. The bottleneck counties are the counties with the smallest capacity to demand ratio and as stated in Results section, these counties end up receiving an amount of food equal to their capacities whereas other counties get penalized if equity is enforced.
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There are some assumptions made in this study. First, it is assumed that the demand, supply and capacity are deterministic. This initial assumption is appropriate as the purpose of this study is to understand the general behavior and structural properties of this network flow problem. This assumption will be relaxed in our future studies. Also, in the case study, we focus on one particular food group. In our future studies, we will incorporate other food groups in the model and explore how we can satisfy equity when all groups are considered and we will also examine the solutions when a slight deviation from equitable distribution is allowed.

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