Fighting Hunger and Reducing Waste in Michigan by Addressing Strategic & Operational Challenges in Measuring Food Accessibility

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Fighting hunger and reducing food waste
by addressing strategic challenges in measuring food accessibility

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Project overview and objectives: Food insecurity is a challenging issue in developing and developed countries. Food insecurity is defined by the Food and Agriculture Organization of the United Nations (FAO) as “a situation that exists when people lack secure access to sufficient amounts of safe and nutritious food for normal growth and development and an active and healthy life” (Orgut et al., 2017). The most recent report from the FAO shows that around 800 million individuals overall experience undernourishment (FAO, 2015). In developed countries, food banks collect food donations and distribute them to individuals in danger of hunger. They play an important role from a sustainability point of view by recovering surplus food that might otherwise be wasted (Orgut et al., 2016b). In the United States, Feeding America serves as the nation’s largest non-profit hunger-relief organization. This organization works with 200 food banks across the country that provide food assistance to about 46 million individuals every year (Orgut et al., 2016a).

The food aid supply chain network includes fourdifferent stakeholders: donors, food banks, charitable agencies, and composting facilities (see Fig.1). Food products are secured from a wide range of sources, such as the United State Department of Agriculture (USDA), food manufacturers, wholesalers, retailers (e.g. grocery chains and supermarkets), farms, and individuals. Donated food products are not salable but still edible even if they are close to their expiration date. Donated food may come from a farmer with surplus agricultural produce or the one whose products are not visually appealing, from a retailer who over-ordered, or from a distributor who experienced damages during transportation (e.g. damaged packaging). While some donors deliver the donated products to local food banks, others ask food banks to send their vehicles to collect food products from their plants. In addition to food donations, there are also individuals and businesses that donate money. Food banks mostly use these financial donations to purchase food items to supplement donations.

Each food bank operates a warehouse which serves as a collection and distribution point for food donations. Food bank warehouses may vary in terms of size, infrastructure, and storage capacity. Three types of food are stored in food banks which require different storage spaces: dry products (e.g. canned goods), refrigerated items (e.g. dairy products), and frozen products (e.g. meat). Incoming food donations are inspected for quality, sorted, stored, and prepared for delivery. Unusable food items are sent to composting facilities.

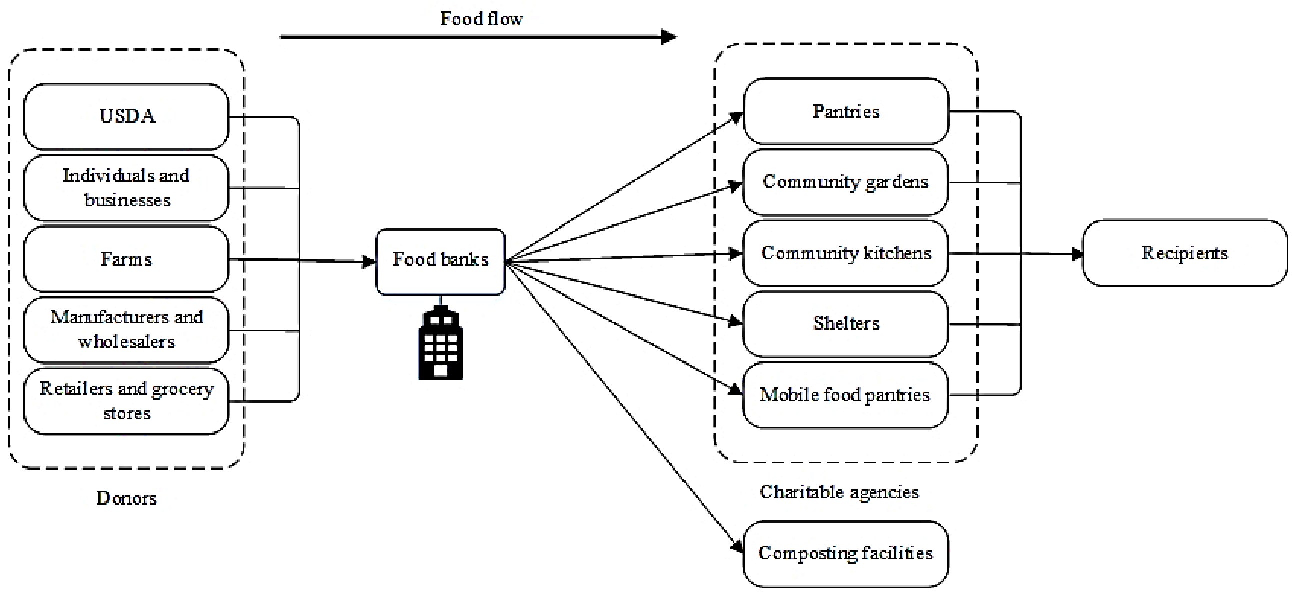

Fig. 1. An illustration for structure of a typical food aid supply chain network (partially adopted from Greater Lansing food bank website).

Food banks may directly distribute food items among people in need or deliver them to charitable agencies. In the latter case, agencies will distribute the food among recipients. Given that a food bank must provide access to donated food to each charitable agency it serves in an equitable manner, food delivery points or sites can be used. Food delivery points or sites increase food access to charitable agencies (Davis et al., 2014). Each food bank either maintains its own fleet of vehicles for food collections/deliveries or rents vehicles if needed. Vehicles differ in size and equipment (e.g. refrigerated, non-refrigerated). Vehicles may also be used to transport food from one food bank to another. This happens when a food bank receives a large quantity of a food product that exceeds the needs of charitable agencies supplied by that local food bank, while another food bank faces a shortage of the same product. Each food bank redistributes donated products to a set of charitable agencies such that they either distribute the food that they receive to people in need or use the food products to prepare meals. Food banks try to supply food products that best meet the nutritional needs of recipients (Martins et al., 2011). For example, items delivered to elderly care centers differ from items prepared for daycare providers.

The aforementioned virtues for food banks operations point to the need for decision making in the supply chain of food banks to answer the following questions: (1) What is the long-term plan (strategic goals) to establish a food-aid supply chain network design? (2) What is the medium-term plans of food aid supply chains?, and (3) From an operational perspective, what is the short-term goal and transportation schedule? In this project, we mainly focus on strategic goals, i.e., network design of food-aid supply chain networks. More specifically, the objective of this research is to present an analytical framework to minimize transportation costs while addressing the following questions: (1) where should (a) new food banks be installed? (2) which supply sources (new and existing food banks) should feed each county?

Strategic decision making: In this section, we discuss the strategic phase focusing on facility location decisions. Facility location decisions play an important role in the strategic design of supply chain networks. In general, facility location concerns the geographical location and optimal placement of facilities for a specific organization. To this end, it is a strategic decision related to the arrangement of the manufacturing network (Chen et al., 2014). Chopra et al. (2013) explains that factors influencing food bank network design decisions include but are not limited to strategic factors (e.g. minimizing cost versus maximizing responsiveness), technological factors (e.g. transportation and logistics technology, storage technology), macroeconomic factors (e.g. tax incentives, freight and fuel costs), and infrastructure factors (e.g. labor and land costs, availability of sites and labor, proximity to transportation terminals, highway access, congestion, and local utilities). The facility location problem involves a set of spatially distributed customers and a set of facilities to serve customer demands. Possible questions to be addressed are: (1) which facilities (e.g. food bank, charitable agencies, food delivery points or sites) should be used (opened)? (2) Which customers should be serviced from which facility (or facilities) so as to minimize the total costs? (Melo et al., 2009).

To the best of our knowledge, the only paper in the literature that focused on determining the optimal location of food banks is Martins et al. (2019) while other papers addressed determining the optimal location of food delivery points or sites. In the food aid supply chain, many food banks serve more than a hundred charitable agencies, with some charitable agencies located in remote parts of the service area. Since food banks primarily make food available to agencies through on-site warehouse shopping, distance limits the ability of an agency to shop on a regular basis. In addition, food bank locations have been determined by past policies, regulations, and food insecure population that may have changed over the time. Another barrier that many charitable agencies face is the limited access to refrigerated vehicles for transporting food (Davis et al., 2014). To solve the problem, some papers including Solak et al. (2014), Davis et al. (2014), Rancourt et al. (2015), Ghoniem et al. (2013), Reihaneh and Ghoniem (2018) defined food delivery points where charitable agencies can receive food deliveries from food banks. Martins et al. (2019) addressed the redesigning of the existing network of food banks. In this respect, redesigning the network of food banks includes deciding to close existing food banks or open new food banks at potential sites. In their model, the food bank status could be changed once over the predefined planning horizon (i.e. if a new facility is established at a candidate location it cannot be closed afterwards). The authors proposed a multi-objective model that incorporates the three aspects of economic, environmental, and social issues in the decision-making process.

There are also several studies in the literature focusing on determining food delivery points. One of these studies is the work conducted by Solak et al. (2014) in which charitable agencies are within a 30-mile radius of the food bank's warehouse, since agencies further away find it difficult to drive in to obtain the food. Agencies place orders with the food bank (typically ranging from 1 to 5 pallets), then the food bank delivers pallets of food by truck to multiple "drop" sites within the service area. The charitable agencies would then travel a reasonable distance to pick up the food they ordered. The authors developed a model that simultaneously selects a set of delivery sites and assigns agencies to selected sites.

Rancourt et al. (2015) conducted a study that solved a location problem in food-aid distribution in Kenya. They presented location models to determine where to locate a set of distribution centers that are uncapacitated and temporary, how much food to deliver to them, and which population they should serve. The food-aid supply chains in their paper composed of several main warehouses located in strategic regions to serve as storage facilities. The food is transported to distribution centers from main warehouses and directly distributed to the vulnerable population. Davis et al. (2014) is another example of the studies that considered food delivery point (FDP). The particular feature of their food delivery points was that the collection and delivery sites are collocated. They developed the model to determine which locations to use as FDPs, as well as how to schedule both collection from food donors and deliveries to charitable agencies via the selected FDPs. In Davis et al. (2014) a food delivery point could be the location for both delivery and pickup of donated food while in studies conducted by Ghoniem et al. (2013) and Reihaneh and Ghoniem (2018), the food delivery points are different from charitable agencies. Ghoniem et al. (2013) defined delivery sites that are usually parking lots and focused on sequential visits to a set of selected delivery sites to supply donated food to the charitable agencies. The authors referred to the charitable agencies as customers and addressed the model in concern of customers (i.e. charitable agencies) that travel from their respective locations to their assigned delivery sites. Reihaneh and Ghoniem (2018) identified intermediate delivery points to which vehicles are routed and charitable agencies are assigned. The amount of food supplied to an intermediate delivery site is determined by the aggregate demand of the charitable agencies assigned to it. Each vehicle is loaded at the central depot, visits a subset of delivery sites, and returns to the depot. On the other hand, the assigned charitable agencies traveled to selected intermediate delivery sites to satisfy their demand.

Objectives: There is a difference between the objectives of decision-makers in for-profit and non-profit food distribution supply chains. In the for-profit supply chain, the objective is to maximize the profit while meeting the demand. However, in the nonprofit supply chain, the amount of donated food (supply) is often lower than total demand; therefore, satisfying the demand is not a feasible option (Orgut et al., 2018). Three common objectives in food aid supply chain models are equity, effectiveness, and efficiency which are explained in the following paragraphs.

Equity implies serving the needs of the customer fairly. The definition of the term “equity” is subjective and can have different implications for different systems (Stone, 1997, Lien et al., 2014). For food banks, a common measure of equity is to ensure that each food-insecure person in their service region receives the same amount of food (Orgut et al., 2016b). Efficiency in supply chain management is traditionally defined as “the inverse of the cost of making and delivering a product to the customer” (Chopra and Meindl, 2013). In the context of non-profit food distribution, cost is driven by the resources required to collect, manage and distribute donated food (Orgut et al., 2016b). Effectiveness measures the ability to meet the needs of the end customer. In the food aid supply chain, effectiveness is measured as a function of meeting hunger need (at the individual level) through food distribution while simultaneously maximizing the yield of the donated supply (i.e. minimize waste) (Orgut et al., 2016b). It needs to be pointed out that the objectives of equity, effectiveness, and efficiency are in conflict with one another and to address food distribution of food banks supply chain, there is always a trade-off between these three objectives.

Several studies consider various criterion for measuring equity, effectiveness and efficiency. The equitable and effective allocation of donated food has received growing attention in the food banks literature. For example, in Orgut et al. (2016a), effective distribution of donated food is defined as minimizing the amount of undistributed supply by ensuring delivery of usable and healthy food on time to the food insecure population. In this study, equity means minimizing the absolute deviation between the need of counties and the proportion of food delivered. Orgut et al. (2018) introduced another equity measure in which the portion of donated food delivered to a county of the service area is equal to the portion of the total county’s relative need. Orgut et al. (2016a) developed a model that controls the total level of equity in the system while in Orgut et al. (2018) the proposed model controls equity only at individual counties. Lien et al. (2014) and Balcik et al. (2014) defined equity as fill rate which means the ratio of the allocated amount to observed demand.. Rey et al. (2018) incorporated envy-freeness as the equity criterion. Envy-free allocation is defined as all the charitable agencies receive the same amount of donated food or the needs of charitable agencies are satisfied if the amount of delivered food is less than maximum amount.

Nair et al. (2016a) and Nair et al. (2017) used *utilitarian* and *egalitarian* terms for efficient and equity food distribution objectives. *Utilitarian* objective aims at maximizing efficiency of the logistical system, which is maximizing the total utility of the delivery customers. *Egalitarian* aims at maximizing the utility of the least-satisfied delivery node (Nair et al. 2017). Eisenhandler and Tzur (2019a) and Eisenhandler and Tzur (2019b) defined a term called “wealth” of each charitable agency to measure equity which means the number of units supplied to it per individual. For the purpose of measuring the effectiveness in their study, they defined the total number of units supplied to all charitable agencies. Martins et al. (2011) considered the equity for a global satisfaction of needs through the received donated product for every food-insecure individual.

From the efficiency perspective, Solak et al. (2014) studied efficiency by minimizing the travel costs of the food banks' delivery vehicles. The authors discussed minimization of the travel cost of charitable agencies to the assigned drop sites (e.g. food delivery point). Other studies that considered the efficiency are Ghoniem et al. (2013) and Reihaneh and Ghoniem (2018). They represented efficiency as the objective function by minimizing a weighted average of the distances traveled by vehicles and charitable agencies to their correspondent delivery sites.

In terms of objective function, there are some studies that focused on single objective, while some have considered multi-objective in food distribution of food banks. In single objective papers, Davis et al. (2014) presented an objective function which minimized the number of activated food delivery points. Nair et al. (2016b) discussed minimizing total transportation cost while satisfying certain operational constraints. Another study in which the authors considered single objective is Nair et al. (2018). They discussed minimizing the maximum difference in pickup and delivery demand service per day during the planning horizon.

In a multi-objective perspective, Rey et al. (2018) incorporated a bi-objective problem that finds the least deviation from an equality allocation and minimizes the total travel cost. The authors applied the weighted-sum method to solve the problem. Another study is Rancourt et al. (2015) that considered minimizing the total cost in three components: (1) access cost for the food insecure population, (2) transportation of supply from the main warehouse to the distribution centers and (3) distribution centers' management and hand-out cost. In Nair et al. (2017), the authors introduced a multi-objective optimization problem which includes utilitarian (i.e., efficiency), egalitarian (i.e. equity), and deviation based. They used goal programming-based formulation to present a solution to the problem. The study by Martins et al. (2019) addressed economic, environmental and social concerns in food aid supply chain networks. The economic component includes minimizing the sum of the cost of supporting charitable agencies, cost of operating storage area, handling products at the food bank and the cost regarding unused transport capacity. The environmental concern includes considering the total value of food waste and CO_2 emissions due to the trips undertaken by food bank vehicles. The social concerns include addressing the total number of charitable agencies that were initially awaiting support and that start to receive food assistance, in line with measuring the total deviation from the reference budget for network redesign and the value of the social work created by the operation of food banks. Table 1 presents a summary of the literature on objective function in food aid supply chain.

Table 1. Summary of existing literature on objective function of food-aid supply chains.

Reference	Single objective	Multi objective	Objective function		
			equity	efficiency	effectiveness
Bartholdi et al. (1983), Gunes et al. (2010), Davis et al.(2014), Nair et al. (2018), Nair et al.(2016b)	✓		✓		
Yildiz et al. (2009), Yildiz et al. (2013)		✓		✓	✓
Martins et al. (2011)	✓		✓		
Ghoniem et al. (2013), Reihaneh and Ghoniem (2018)		✓		✓	
Balcik et al. (2014), Lien et al. (2014), Orgut et al. (2016a), Orgut et al. (2018), Eisenhandler and Tzur (2019a), Eisenhandler and Tzur (2019b)	✓		✓		✓
Solak et al. (2014), Rancourt et al. (2015)		✓		✓	
Nair et al. (2016a), Nair et al. (2017)		✓	✓	✓	
Orgut et al. (2017), Rey et al. (2018)		✓	✓		✓
Martins et al. (2019)		✓	✓	✓	✓

Our proposed analytical framework: We present a generalized analytical framework that can be applied for any food-aid supply chain network. The first step is to prepare a .csv file including the following information (Fig. 2):

A	B	C	D	E	F	G
agency_id	agency_name	agency_address	x-coordinate	y-coordinate	demand	food bank

Fig. 2. Preparing .csv file for food-aid network design problem

The first column presents the identification code corresponding to the charitable agency. Each charitable agency is recognized by a code (number). The numbers start from 0. The second column presents the name of the agency. As mentioned before, the agency can be a school, church, soup kitchen, etc. The third column presents the physical address of the agency. By having this information, one can retrieve the information related to the next two columns. The fourth and fifth columns are x- and y-coordinates of the agency. These are the latitude and longitude of the agency. In order to find these numbers, it is sufficient to enter the physical address of each agency in a Google map search, right click on the destination sign, select “What’s here?”, and then the x- and y-coordinates of the location appear on the map (Fig. 3).

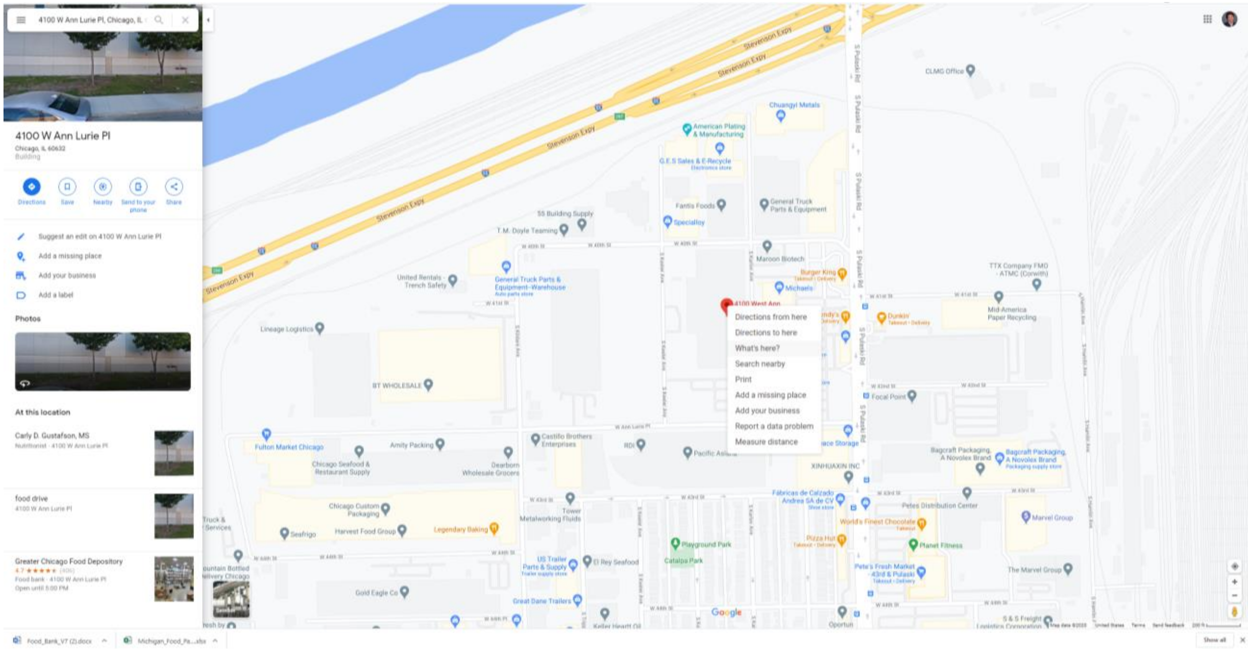

Fig. 3. Using Google map search to find x- and y-coordinates of a location

The sixth column presents the weekly demand of each agency. The last column specifies the food bank that is currently designated to the agency to satisfy its demand. The information related to the location of charitable agencies can be obtained from https://www.foodpantries.org/. Although this website provides the location of agencies, it does not provide the information related to the weekly demand of each agency. In order to estimate weekly demand, we applied the data related to the demand of each county instead of each agency. This data can be retrieved by following these three steps:

1. Retrieving the data related to the food insecure population in county A from http://map.feedingamerica.org/county/2018/overall. This website provides the food insecure population in each county for years 2016, 2017, and 2018.
2. Considering the amount of food (in pounds) that an individual needs per week.
3. Calculating total amount of food (in pounds) required to serve food insecure population of county A for one week.

In addition, each state has its own service coverage map, specifying which county is allocated to the service region of which food bank. We note that each state has a number of food banks serving counties of the state. The service coverage map of each state can be found on their own website. Finally, in our proposed analytical framework, we consider several assumptions to simplify the model:

1. The food delivery point of each county is located at the center of each county. The x- and y-coordinate of this point can be obtained from Google map (mentioned above). We consider this assumption since we do not have access to the detailed data of weekly demand of charitable

agencies. Having access to the data of charitable agencies, we could use the gravity model (Chopra et al., 2013) to determine the optimal delivery point in each county. However, the impact of this assumption on determining the optimal location for the new bank is quite insignificant, since the gap between the total distance traveled to the center of each county and the total distance traveled to the optimal delivery point of each county is not huge.

2. In each trip of a truck, only the demand of one county is satisfied. We consider this assumption since we do not have access to the weekly itinerary of trucks. In practice, a truck may be loaded at a food bank to serve more than one county, but since we do not have access to the data related to each truck's capacity and visiting frequency of agencies by trucks, it is quite reasonable to assume that each truck only serves one county in each trip. We expect that this assumption significantly impacts the optimal solution. We explain this impact by an example. Suppose in scenario (1), the demand of counties A, B, and C are satisfied by 3 separate trips, while in scenario (2), the demand of counties could be satisfied by only one trip. Then, the total distance traveled to the center of counties A, B, and C in scenario (1) is much larger than the total distance traveled to the center of the counties in scenario (2).
3. The capacity of trucks is relaxed. Suppose a truck has the capacity of x pounds commodity and county A has the weekly demand of x', where $x' > x$. Therefore, $\left\lceil \frac{x'}{x} \right\rceil$ number of trucks are required to satisfy such demand. Since trucks of a food bank may differ in terms of size, capacity, and type (i.e., refrigerated, non-refrigerated), and we do not have access to such detailed data, we relaxed the capacity of trucks and assume that the transportation cost of a pound of food is a ratio of its total traveled distance. The latest data from the American Transportation Research Institute (ATRI) reports that the average trucking cost per mile-ton in the U.S. is $1.82. We use this assumption in our calculation for transportation costs in our mathematical modeling. This assumption may impact the total transportation costs, but its impact is much less than the impact of assumption 2.
4. The storage capacity of a food delivery point in a county is always greater than its weekly demand. This assumption prevents any storage capacity constraint violation. In fact, this assumption simplifies the problem not to be involved in complications of storage capacity constraints and does not impact the final solution (optimal location for installing a new food bank).
5. Single commodity is transported from food bank to agencies. This assumption prevents any sort of complication (e.g., different type of trucks for transporting different type of commodities) that may occur for multi-commodity network design problem and should not significantly impact the final solution.
6. All calculations are based on the data related to the food insecure population reported in 2018. Since we only have access to the data related to food insecure population of each county for three

years, we are not able to accurately estimate the future demand by the data for these limited number of years. Therefore, we decided to work with the latest data (i.e., 2018). The demand of each county significantly impact the final solution, since the total transportation cost is calculated by the summation over the quantity of demand of counties (in ton) multiply by the distance traveled (in mile) multiply by the transportation cost per mile-ton.

7. We assume that opening a new food bank is a must, and the installation cost of a new food bank is the same in all counties. We note that in the classical facility location problem, one can address the following questions: is opening a new facility recommended? If so, where should this facility be installed? Finally, which agencies should be assigned to the new facility, and which agencies should receive the service from the existing facilities? If historical demand data is available, one can determine the number of years after which the transportation cost savings from installing a new facility outweigh the installation cost of the new facility. However, since we do not have access to such rich data, we do not include the installation cost in the objective function, assume that installation cost is the same in all counties, and opening a new facility is definitely required. Removing this assumption may significantly impact the optimal solution if there is a significant difference between the installation cost of a new food bank in various counties.

After finding the latitude and longitude of the center of each county, we calculate the geographical distance between nodes *i* and *j* (denoted by $\delta_{i,j}$) by Haversine formula (Eq. 1).

$$\delta_{i,j} = 2R.\arcsin\left(\sqrt{sin^2\left(\frac{\pi}{180}\Delta lat\right) + \cos\left(\frac{\pi}{180}lat_i\right).\cos\left(\frac{\pi}{180}lat_j\right).sin^2\left(\frac{\pi}{180}\Delta lng\right)}\right) \quad (1)$$

In Eq. (1), lat_i and lng_i stand for the latitude and longitude of node i, $\Delta lat = \frac{lat_i - lat_j}{2}$, $\Delta lng = \frac{lng_i - lng_j}{2}$ and $R = 3963.189\ miles$.

From Eq. (1), we obtain the geographical distance between counties i and j. We denote this distance by $dis(i,j)$ with the unit of mile. Since this distance is the length of the arc connecting node i to node j, we need to make sure that such physical connection exists. If for any reason (e.g., the existence of a lake or river between two regions) such physical connection does not exist, we need to find a third node (e.g. node k) by which we could connect nodes i and j together. Then, $dis(i,j) = dis(i,k) + dis(k,j)$. Also, let $d(i)$ denote the food demand of county i with the unit of pound. As mentioned before, according to the ATRI, the average trucking cost per mile-ton in the U.S. is \$1.82. Then, one can calculate the cost of transporting food from the food bank located in county j to county i by $1.82 \times d(i) \times dis(i,j)$. Let decision variable $x(i,j)$ be 1 if and only if county i is assigned to the food bank located at county j, and 0 otherwise. Also, let decision variable $y(j)$ be 1 if and only if the food bank at county j exists. Then, we can write the total transportation cost which is the objective function of our optimization model as follows:

$$Min \sum_{i,j} 1.82 \times d(i) \times dis(i,j) \times x(i,j) \tag{2}$$

We also list the following constraints corresponding to our optimization problem:

$$\sum_{j} x(i,j) = 1 \qquad \forall i \tag{3}$$

$$y(i^*) = 1 \qquad \forall i^* \tag{4}$$

$$\sum_{j} y(j) = n \tag{5}$$

$$x(i,j) \leq y(j) \qquad \forall i,j \tag{6}$$

$$x(i,j) \in \{0,1\}, y(j) \in \{0,1\} \qquad \forall i,j \tag{7}$$

Constraint (3) guarantees that each county is assigned to only one food bank. Constraint (4) ensures that the food bank of county i^* (the county at which the current food bank is located) is open. We note that food bank at county i^* exists and will remain open throughout the planning horizon. Constraint (5) is the key constraint allowing us to have n food banks in the system. Let us assume that n_1 number of food banks are currently open and working in the state. Then, $n - n_1$ is the total number of food banks we are interested to install in the state in the future. Constraint (6) guarantees that county i is assigned to food bank j if and only if food bank j (food bank at county j) exists. Constraint (7) ensures the binary definitional constraints of variables. In addition to these constraints, one can impose the storage capacity of the food bank into the model by including constraint (8):

$$\sum_{i} x(i,j) \leq cap(j).y(j) \qquad \forall j \tag{8}$$

Constraint (8) ensures that the demand of counties allocated to food bank j does not exceed the storage capacity of the food bank. We mathematically model this optimization problem in General Algebraic Modeling System (GAMS) distribution 23.

Numerical example: The initial goal of this project was to develop an analytical framework that could be used to analyze and propose optimum locations for new or existing food bank facility locations within Michigan. Detailed data collection was planned across many dimensions in order to build the most comprehensive model possible. The questionnaire including the following:

Questions related to donors:

- Do you have considerable fluctuations in supply (donated food) in various time of the year (week by week, month by month)?
- Do you know in advance how much food is going to be donated when you send the truck to the donor's location? Or everything is revealed once the truck driver arrives at their facility?
- Do you usually send more than one truck to a donor's facility to pick up donated food?
- How about frequency of visits? Is it daily, weekly, or bi-weekly?
- Do you have donors that would like to send their donated food to specific counties? For example, some restrictions on where their donated food is used.
- Detailed data on:
    - Geographical location of each donor
    - Weekly/monthly(?) amount of donated food (in pounds?) of each donor

Questions related to food banks:

- Are food bank facilities places for collecting, storing, and distributing food or can they be a place for picking up the food by recipients as well? In other words, can food banks have their own demand?
- Is it possible that donors directly send the food to agencies without unloading/loading the food at food banks?
- Detailed data on:
    - Geographical location of food banks
    - Storage capacity of food banks for dried, refrigerated, and frozen foods

Questions related to food recovery agencies:

- Is there any charitable agency that is served by more than one food bank?
- How about frequency of visits? Weekly? bi-weekly? Monthly?
- Do you deliver food to "food delivery points"? Food delivery points are locations from which agencies pick up the food. Some food banks deliver food to food delivery points instead of delivering them to agencies.
- Does the demand of an agency vary over the time of year?
- Do you know the demand of each agency in advance when you dispatch your truck to serve that agency? In other words, when do you learn how much food an agency needs? In some research papers, they assume that the demand will be known once the truck driver arrives at the agency location. Then, depending on the current inventory of the agency, they ask for various amount of food. Before that, the food bank does not know the demand.

- Detailed data on:
  - Geographical location of agencies
  - Storage capacity of agencies for various types of food
- What are your criteria for distributing/assigning the food among charitable agencies? According to the literature, equity, efficiency, and effectiveness are three important objectives of food banks. Do you distribute the food based on counties' population, food insecure population, minimizing transportation costs, or serving more people (no matter they are all from the same county)?

Questions related to donated food

- Types of food (fresh, frozen, perishable-non-perishable). What is your classification?
- Do you sort/rank food based on their perishability? Quality? Please describe any specific regulation that is used for sorting donated food items.
- Do you have any specific regulation for storage and transportation of food? For example, from the literature, perishable foods above 40-degree Fahrenheit for more than 2 hours should be discarded. Knowing These regulations, particularly in transportation operations, is very important from the mathematical modeling perspective.
- What is the unit of food for your food bank? Number of meals? Pounds? Number of food pallets?
- Do you face any surplus food? Do you redistribute them or discard them?

Questions related to transportation/storage

- Do you have same-day delivery (you deliver food items to charitable agencies the same day as you receive it from food donors)? Or do you store them at food bank facilities for a particular time?
- What is the sequence of pickup/delivery? Do you deliver food to agencies first and then pick up food from donors? Some research papers assume this sequence for safety to deliver usable food to agencies first and then pick up the donated food (mixed of usable and unusable food) from donors.
- Do you transport particular food by particular trucks?
- Do you have different trucks (various in terms of capacity, refrigerated/non-refrigerated)? If so, please explain it by details.
- Does a truck take more than one route per day? (A route starts from a depot and ends at the depot again). In other words, do trucks visit depot for several times per day for loading/unloading?
- How do you decide about the sequence of deliveries and the amount of food to be unloaded for each agency/county?
- Do you have a mix of pickup and delivery in one route?

- Please provide the detailed information on the number of trucks, type, and capacity of each. Do they work every day, or the number of working trucks varies over the days of the week (depending on volunteer truck drivers)?
- Can you load various types of product in one truck?

However, due to the Covid-19 pandemic and the resultant increased demands on the Michigan food bank network, this data collection request and in-person facility visits were understandably not supported at this time. Due to this limitation, we decided to simplify and demonstrate the model using data found on public websites from the state of Connecticut, a seemingly less complex food aid supply chain network. In this way the analytic principles of the model could still be demonstrated. Table 2 presents the information related to counties in the state of Connecticut. This includes county identification, county name, x- and y-coordinate of the center of the county, weekly demand of the county (we assume that each individual receives 4 pounds of food per week), and the food bank allocated to the county. According to https://www.ctfoodbank.org/, there is only one food bank in the state of Connecticut. The food bank is located at Wallingford, in New Haven County and serves all 8 counties.

Table 2. Information related to the food-aid network of Connecticut.

county id	county name	x-coordinate	y-coordinate	weekly demand	food bank
1	Fairfield	41.289595	-73.341188	373080	New Haven
2	Hartford	41.832077	-72.748299	420200	New Haven
3	Litchfield	41.816744	-73.232678	71560	New Haven
4	Middlesex	41.485372	-72.554514	63080	New Haven
5	New Haven	41.434082	-72.928046	417560	New Haven
6	New London	41.519584	-72.081712	126680	New Haven
7	Tolland	41.861528	-72.327225	55920	New Haven
8	Windham	41.842616	-71.994136	55600	New Haven

Computational results: The GAMS code developed for this project can be found here: https://www.researchgate.net/publication/344462338_food_bank_network_design_--_Case_study_of_the_State_of_Connecticut. After solving the problem to optimality, we found that if we are asked to install only one new food bank, it should be installed at "Hartford" county. The county id corresponding to this county is 2. Table 3 shows the optimal assignment of each county to each food bank once a new food bank is installed. We observe that 5 counties are assigned to the new food bank (located at Hartford county), while the remaining 3 are assigned to the existing food bank located at New Haven county.

We are also able to calculate the cost savings by installing a new food bank. If only New Haven food bank serves the whole region, we estimate the annual transportation cost of $ 1,750,000, while once Hartford food bank is installed, we estimate the annual transportation cost of $1,000,000. Therefore, we can save approximately $750,000 from transportation costs annually.

We note that the results presented in Table 3 are theoretical and based on constraints (3)-(8), assumptions (1)-(7), and the data presented in Table 2. As mentioned before, among these assumptions and constraints, assumptions (2) and (6) have significant impacts on the optimal solution since they significantly impact total transportation costs, i.e., the objective function of the facility location problem. Any change or update in these assumptions may affect the optimal location of installing new food banks in the food aid supply chain network.

Table 3. Assigned counties to designated food banks (one existing located at New Haven county) and one new food bank (to be installed at Hartford county))

county id	**county name**	**assigned food bank**
1	Fairfield	New Haven
2	Hartford	Hartford
3	Litchfield	Hartford
4	Middlesex	New Haven
5	New Haven	New Haven
6	New London	Hartford
7	Tolland	Hartford
8	Windham	Hartford

We can also analyze the impact of installing two more food banks instead of one to this supply chain. We run the algorithm again for 3 food banks in total to obtain the optimal solution. Table 4 shows the optimal assignment of each county to each food bank once two new food banks are installed. The results show that these two food banks should be located at "Fairfield" and "Hartford" counties.

Again, we can calculate the cost savings by installing new food banks. If new food banks at Hartford and Fairfield are installed, we estimate the annual transportation cost of approximately $570,000. Therefore, we can roughly save $1,180,000 from transportation costs annually.

Table 4. Assigned counties to designated food banks (one existing (located at New Haven county) and two new food banks (to be installed at Hartford and Fairfield counties))

county id	**county name**	**assigned food bank**

1	Fairfield	Fairfield
2	Hartford	Hartford
3	Litchfield	Hartford
4	Middlesex	New Haven
5	New Haven	New Haven
6	New London	Hartford
7	Tolland	Hartford
8	Windham	Hartford

Conclusion: In this research project, we developed an analytical framework to identify where to install a new food bank(s) in food-aid supply chain networks to minimize transportation cost. We tested our model based on the data retrieved from http://map.feedingamerica.org/county/2018/overall. This data reports food insecure population of each county for years 2016, 2017, and 2018. This data is not rich enough to predict future food insecure population for coming years; however, we used the data reported for 2018 to test our model. The initial goal of this project was to develop an analytical framework that could be used to analyze and propose optimum locations for new or existing food bank facility locations within Michigan. Detailed data collection was planned across many dimensions in order to build the most comprehensive model possible. However, due to the Covid-19 pandemic and the resultant increased demands on the Michigan food bank network, this data collection request and in-person facility visits were understandably not supported at this time. Due to this limitation, we decided to simplify and demonstrate the model using data found on public websites from the state of Connecticut, a seemingly less complex food aid supply chain network. In this way the analytic principles of the model are able to be demonstrated.

Our model has limitations that can be improved by future research works: (1) we assumed the food delivery point of each county is located at the center of each county, because we did not have access to the detailed data of weekly demand of charitable agencies. Having such detailed information, we could determine the geographical location of food delivery points more accurately; (2) each truck serves only one county per trip. Having access to the information related to the number and capacity of trucks as well as visiting frequency of agencies allows us to relax such constraint; (3) We assumed that the transportation cost is the ratio of total distance that a truck travels. In this case, we assume that the transportation cost is not influenced by the amount of food we load into the truck (fully loaded versus partially loaded trucks). For future research, it would be interesting to analyze the costs when trucks are not fully loaded from the central depot; (4) The storage capacity of food delivery points has not been considered into our model. We assume that we never face oversaturation of warehouses when trucks unloaded commodities at a food delivery point; (5) for simplicity, we consider a single commodity, while studying multiple commodity network design problem respecting various types of trucks transporting such commodities would be more realistic to explore; (6) We only consider the data related to the food insecure population in 2018. It would be more accurate if we could have access to such data for several years to be able to predict the food insecure population for coming years; (7) The decision support model does not provide an answer for this question that whether or not installing a new food bank is beneficial. If that was the case, the installation cost of a new food bank should be included into the objective function. Moreover, historical demand data was required such that we could calculate after how many years the savings from transportation costs overweigh the fixed installation cost.

Among the foregoing assumptions, assumptions (2) and (6) significantly impact the optimal solution, i.e., optimal location for installing a new food bank. Regarding assumption (2), it is clear that a truck serving multiple counties within its trip can reduce significant transportation costs in comparison to a truck serving a single county within each trip. Regarding assumption (6), since demand plays an important factor in calculating transportation costs, we expect that its variation significantly impacts the final results.

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