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Equitable distribution of perishable items in a food bank supply chain

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Abstract

In the United States, food banks play an important role in helping to reduce the rate of food insecurity by distributing donated food among the population in need. One of the challenges that food banks face is to equitably distribute food donations among their clients such that, ideally, each recipient receives the same amount of food. They aim to do so while minimizing waste that occurs due to spoilage and capacity limitations. Perishable food items present specific challenges since they are susceptible to spoilage and need to be distributed before their expiry dates. Based on our longstanding partnership with a large food bank located in the southeastern United States, we present a capacitated, multiperiod, multiproduct network flow model to help them equitably and effectively distribute perishable food donations among the food-insecure population in their service region. The model is applied within the context of a case study and reveals managerial insights that would be useful to practitioners. Our findings show that although equity is one of the food bank's highest priorities, inequities cannot be eliminated completely. Given the inevitability of inequitable food allocations in practice, this paper provides food banks guidance on how to strategically control inequities using two approaches: (*i*) by increasing the number of periods for which equity should be satisfied or (*ii*) by allowing deviations from a perfectly equitable distribution. The results show that modest deviations from perfect equity using either approach can lead to significant improvements in both the quality and quantity of food distributed and can also reduce food waste. While approach (*ii*) is preferable, the most desirable outcomes occur when both are applied simultaneously. We also find that county capacities inhibit a food bank's ability to achieve balance between equity and effectiveness when distributing perishables. Our framework provides food banks the flexibility to balance the trade-off between effectiveness and equity based on their preferences.

KEYWORDS
equity, food bank, food insecurity, nonprofit operations, perishable

1 | INTRODUCTION

Daily access to food is one of the most basic human necessities. However, in 2018, about 10.8% of the world's population (roughly 821 million people) experienced *food insecurity*, which refers to limited and/or uncertain access to an adequate supply of nutritious food (United Nations, 2020). Food insecurity not only affects developing countries but also rich ones with well-developed economies and abundant food supply systems (Pollard & Booth, 2019). For example, roughly 11% of the U.S. population experienced some degree of food insecurity in 2018, which corresponds to 37 million people including 11 million children (Coleman-Jensen et al., 2019). To make matters worse, 53 million people in the United States experienced food insecurity in 2021 as a result of the COVID-19 pandemic (Feeding America, 2022). Ironically, a significant amount of food waste also exists amidst the rising food insecurity rates. In 2018, the United States

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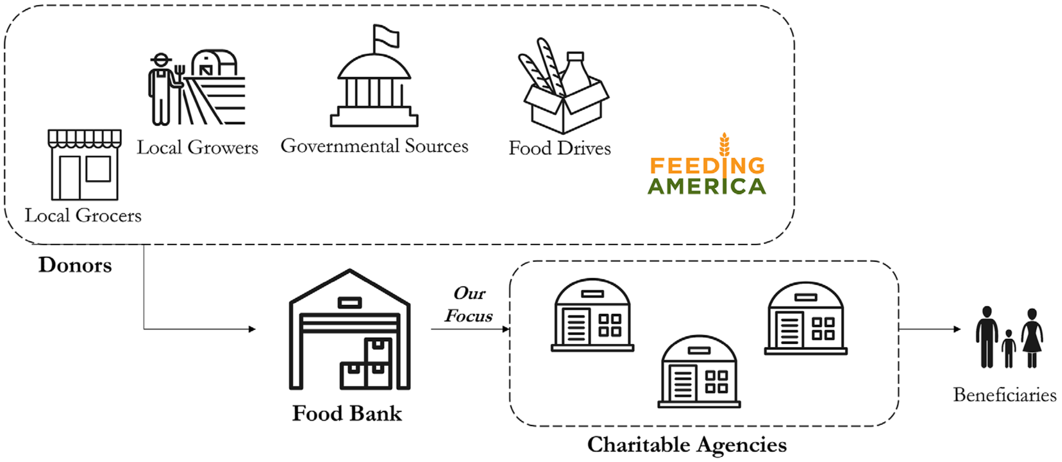


FIGURE 1 General structure of food bank supply chain networks. This study focuses on distribution from the food bank to charitable agencies. [Color figure can be viewed at wileyonlinelibrary.com]

generated over 60 million tons of food waste (U.S. Environmental Protection Agency, 2020), which represents 30–40% of its food supply.

Food banks offer a solution that addresses both food waste and food insecurity. Specifically, food banks and their associated supply chains are able to simultaneously reduce both food waste and food insecurity by repurposing food that would have otherwise been disposed of and distributing it to food insecure populations. Globally, three major food banks networks (The Global FoodBanking Network, European Food Banks Federation, and Feeding America) served 62.5 million people, diverted 2.68 million metric tons from landfills, and prevented 10.54 billion kilograms of greenhouse gas emissions (Global FoodBanking Network, 2019). Food banks are able to accomplish these achievements by coordinating supply chain networks that consist of donors, food banks, and charitable agencies. Figure 1 illustrates the food bank supply chain system in the United States. Food banks acquire food from donors such as nearby farmers and supermarkets, and national sources such as Feeding America, and then facilitate distribution of the donated food to soup kitchens, food pantries, and other charitable agencies where it can be retrieved by individuals and families.

This study is based on operations of an affiliate of the Feeding America food bank network. Feeding America oversees more than 200 food banks and distributes about four billion meals to 46.5 million people annually, making it the largest food bank operation in the United States (Feeding America, 2022). The Feeding America affiliate considered in this study is the Food Bank of Central and Eastern North Carolina (FBCENC), which distributed over 80 million pounds of food to 756,320 people across 34 North Carolina counties in 2019 (Food Bank of Central and Eastern North Carolina, 2020). While the majority of the food procured and distributed by FBCENC is nonperishable dry goods, approximately 35% of it is perishable equating to about 29 million pounds of food annually. As such, this paper concerns the distribution of perishable products such as produce, cold foods, and frozen foods, which are inherently more susceptible to spoilage than nonperishables and therefore pose the greatest risk to exacerbating the food waste predicament described above.

Like most food banks, FBCENC receives and distributes a variety of food types that fall into four categories: dry goods, refrigerated food, frozen food, and produce. In fact, FBCENC handles over 50 food categories. These diverse food donations are received continuously by FBCENC on a daily basis, although scheduled deliveries are arranged in advance for high-volume donors. Food bank staff and volunteer workers inspect, sort, and prepare incoming food donations for storage until they are either shipped to charitable agencies across 34 counties or discarded if they expire before being shipped.

Problem description

This study considers the distribution of food from a single food bank to the counties within its service region in the context of a multiproduct/multiperiod framework. In each period (week), the food bank receives varying quantities of perishable food products from the donors in Figure 1 and then decides how much of each product is distributed to each county. Each perishable food item enters the food bank supply chain at its highest value in terms of freshness in the period it is received by the food bank but deteriorates each period thereafter until it is either scheduled for shipment or loses its value entirely.

FBCENC (and food banks in general) would like to distribute as much food as possible, to as many beneficiaries as possible, as soon as possible. However, there are several factors that make effective and equitable distribution particularly challenging for FBCENC. The first is that charitable agencies within the 34 counties have limited capacity in terms of the amount of food they can receive, store, and distribute to beneficiaries. County agencies rely on local infrastructure to process shipments from the food bank; specifically, they have to provide material handling equipment and manpower for unloading delivery vehicles, physical storage space to hold the food after each delivery from the food bank, and personnel, who are mostly volunteers, to oversee the distribution of food. Each of these resources represents a limitation in terms of how much food the agencies can take on, especially for counties with small populations and high rates of food insecurity.

A second challenge for FBCENC is Feeding America's equity requirements. In order to maintain affiliation with Feeding America, all affiliate food banks (including FBCENC) have to ensure that each county receives its fair share of food and reports the level of equity achieved in their respective service regions. The equity measure used by FBCENC and Feeding America is called *perfect equity* whereby each county receives food in proportion to the food-insecure population they serve, that is, their "fair share" (Sengul Orgut, Ivy, et al., 2016), every period. They measure equity based on the pounds of food distributed per food-insecure person in each county every period. "Fair share" is also dictated by the capacity of each county in terms of the amount of food it is capable of receiving, storing, and distributing. For example, if a county with high food insecurity rate lacks the capacity to receive their fair share of food, then the overall equity achieved in the network is impacted. It is also important to note the trade-off that exists between distributing food equitably and effectively (here, effectiveness refers to the total amount of food distributed and/or the number of beneficiaries served). In practice, FBCENC will often concede deviations from perfect equity in hindsight by distributing available food to counties with unfilled demands and sufficient capacity. However, this redistribution is a result of food left over from the original perfect equity distribution and is, for the most part, carried out in an ad hoc manner. The food bank would likely have a better result in terms of both equity and the amount of food distributed if deviations from perfect equity are strategically planned from the beginning. We examine the advantages and disadvantages of purposeful deviation from perfect equity and then explore options for strategically managing these inequities in ways that achieve the greatest benefit relative to the food bank's tolerance for relaxing perfect equity requirements.

Another challenge that FBCENC and food banks in general have to contend with is the complexity of managing multiple perishable items. These food items are received by the food bank at different times and represent different categories of foods that deteriorate at different rates. Thus, the food bank's supply at any point in time consists of food items at various stages of decay with various amounts of time until expiration. This notion of food quality also brings FBCENC's and Feeding America's traditional interpretation of equity into question. If a food bank distributes the same amount of food to two counties but one county receives all 100% quality (perfect condition) and the other receives 1% quality (nearly expired), is this truly equitable?

Research questions

The above-mentioned challenges experienced by FBCENC motivate the following research questions, all of which will be addressed in the case study presented in Section 4.

1. Are substantial deviations from perfect equity required in order to achieve meaningful improvements in the total amount of food distributed and amount of food wasted?
2. In what ways can food banks strategically manage target deviations from perfect equity to better balance the equity/effectiveness trade-off? What are the effects of enforcing equity over multiple periods as opposed to each period?
3. What implications do food deterioration rates have for setting equity deviation targets?
4. Is it possible for the food bank to achieve equity in both the quality and quantity of food distributed, or is there a trade-off between the two?

The performance of food bank distribution operations is typically assessed in three dimensions: efficiency, effectiveness, and equity (Sengul Orgut, Brock, et al., 2016). This study takes effectiveness and equity into account. We measure effectiveness as the total value of outgoing shipments from the food bank over a multiperiod planning horizon, where value reflects (*i*) the amount of deterioration that has occurred by the time each donated food item is shipped and (*ii*) the total amount of food distributed (measured in pounds). Thus, effectiveness is decreasing in deterioration and time and increasing in quantity. So to achieve the objective of maximizing value, the food bank has to deliver large quantities of recently received foods that have not yet begun to deteriorate. With respect to equity, we formulate a constraint that controls the deviation from perfect equity in two ways: (*i*) by allowing fair share to be achieved over a user-defined, multiperiod time window and (*ii*) by allowing each county to deviate from their fair share up to a certain percentage in each period. We do not consider the efficiency objective in this study. Because for the most part, efficiency means *cost efficiency* in the food bank operations management literature (Hasnain et al., 2021; Islam & Ivy, 2022; Mohan et al., 2013). These costs are generally the operational costs incurred from vehicle routing decisions associated with delivering food items to the agencies within each county. Although budget restrictions exist for such operations, equity, and effectiveness are by far the primary considerations, especially for perishable items that need to be distributed quickly, according to our food bank partner.

We formulate the food bank's multiperiod/multiproduct food distribution operation as a linear programming (LP) problem whose objective is to maximize total value where equity, county capacities, and food supply are constraints. No uncertainty in supply or demand is considered. FBCENC has maintained accurate records of food donations over several years and therefore has a large data repository that can be used to predict daily food donations with a high degree of certainty. To estimate demand, we consider all agencies in each county in aggregate, that is, county-level demands, same as FBCENC. Then, we take demand as the size of the poverty population of each county, which is public data that remains constant during the planning horizons we consider. This approach to representing demand is common in the food bank literature and is also used by Feeding America. We solve the LP model optimally using commercial software.

Contributions

The primary contributions of this study are the practical implications for food bank managers derived from the case study. First, we propose intentional and strategic deviation from perfect equity as an alternative to the after-the-fact and ad hoc approach currently used in practice for balancing the equity/effectiveness trade-off. Two logical alternatives are proposed: (*i*) allow perfect equity to be attained over multiple periods (as opposed to the traditional approach where the goal is perfect equity in each period) and (*ii*) allow a maximum deviation from perfect equity in each period. We also consider (*i*) and (*ii*) in tandem where maximum deviations from perfect equity achieved over multiple periods are permissible. Results from the case study suggest that approach (*ii*) outperforms approach (*i*), but the most desirable outcomes occur when both are applied simultaneously. The case study also reveals that small deviations from perfect equity can lead to noticeable improvements in effectiveness. Through our extensive case study, we explore the impact of these deviations on the different counties in the food bank's service regions and highlight which counties may be disproportionately affected if such policies are followed. We consider FBCENC's actual distribution as benchmark and illustrate the improvements achieved by our model over the current distribution. We also provide a detailed analysis of how various exogenous factors, such as county capacities and product deterioration rates, impact a food bank's ability to achieve equity and effectiveness. Finally, we also introduce a new way for food banks to interpret equity that is based on the quality of food distributed, rather than only quantity which is the common approach. This allows us to examine a new trade-off: the trade-off between quantity and quality when it comes to equity. Collectively, these contributions advance food bank research by adopting a perspective that not only prioritizes reducing food insecurity but food waste as well. We address the complexities of managing multiple perishable products over multiple periods based on the operations of a high-volume food bank distributor (FBCENC), which directly adds value from a practical standpoint.

The remainder of this paper is organized as follows. In the next section, we review related research literature and elaborate upon the above-mentioned contributions. Next in Section 3, we present a LP model to represent the food bank's food distribution problem. Section 4 presents a case study based on the FBCENC data and examines properties of optimal allocation policies by focusing on equity and effectiveness. Section 5 discusses the major practical insights derived from the case study. Concluding remarks are given in Section 6.

2 | LITERATURE REVIEW

We position our work from the perspective of three areas of the operations management literature: (*i*) management of food bank operations, (*ii*) distribution of perishable products, and (*iii*) equitable resource allocation in humanitarian operations.

2.1 | Food bank operations management

Research in food bank operations primarily considers vehicle routing and scheduling for last-mile distribution, an operational problem that focuses on the delivery of food items to the final stage of the food bank supply chain, typically agencies (e.g., Blackmon et al., 2021; Davis et al., 2014). Other studies focus on strategic decisions such as developing policies that increase donations to food banks (Ahire & Pekgün, 2018) or redesigning food bank networks (Martins et al., 2019). This study considers the tactical problem of determining how much food to distribute to each county in a food bank's service area on a weekly basis over a given time frame. As such, the scope of this section is limited to papers that feature tactical decisions made by food banks. More comprehensive coverage of the food bank operations literature is presented in Mahmoudi et al. (2022) and Rivera et al. (2023).

Several studies address the tactical decision problem of allocating food within a food bank's service region. Fianu and Davis (2018) develop a discrete-time Markov decision process (MDP) model in which food donations arrive to the food bank according to a stochastic process and are subsequently distributed to meet deterministic demands (measured as pounds per person in poverty, or PPIP) at each county. They consider three allocation rules from the inventory control literature, and their MDP model identifies which of them is optimal under various conditions. Lee et al. (2017) also present an MDP model to optimize the allocation of food but from the perspective of farm-gleaning operations. In particular, their MDP model seeks to optimize an objective function that takes both PPIP and equity into account, and their model also considers uncertainty in both supply (the amount of food the farm donates) and labor (the number of volunteer gleaners available). Alkaabneh et al. (2021) develop a resource allocation framework for food banks using approximate dynamic programming that allocates food donations in a way that maximizes total nutritional value. Gómez-Pantoja et al. (2021) consider the allocation of a set of food items by food banks to beneficiaries while taking into account the beneficiaries' priorities, calories and nutrition received, and compatibility with the received products. Islam and Ivy (2022) study the problem of allocating the counties to branches in a food bank's service region to minimize cost while seeking an equitable and effective food distribution policy. Hasnain et al. (2021) develop a noninteractive preference elicitation algorithm for determining a food bank's preference on the objectives of equity, effectiveness, and efficiency and examine the resulting food allocation policies. The series of papers by Sengul Orgut, Ivy, et al. (2016) and Sengul Orgut et al. (2017, 2018) are the ones that are the closest to ours. They consider the optimal allocation of donated food items to the counties in a food bank's service region under both equity and county capacity constraints. The first study, Sengul Orgut, Ivy, et al. (2016), introduces a deterministic network-flow model to determine optimal food distribution policies, while the latter two extend that work by considering stochastic county capacities.

All of the above studies focus on nonperishable food items such as dry goods. We extend these studies by considering the specific challenges of managing multiple perishable products over multiperiod planning horizons within the context of a case study that focuses on practical implications and insights. Recent studies also address food bank distribution over multiple periods (Blackmon et al., 2021; Eisenhandler & Tzur, 2022), but these are based on operational settings. Also, Feng et al. (2022) introduce a general-purpose multi-product resource allocation model that has implications for food bank operations.

2.2 | Distribution of perishable products

Perishables refer to products such as vegetables, fruits, radioactive and chemical materials, and pharmaceuticals that lose their value over time (Chaudhary et al., 2018). Although accounting for product perishability within the context of humanitarian operations seems to represent a gap in the research literature, this topic has been studied quite extensively in operations management. There are two streams of research related to this area: (*i*) studies that consider perishable products, which refer to items such as electronics or fashion goods that suddenly lose their value and become obsolete and (*ii*) studies that examine deteriorating items such as food products that gradually deteriorate over time. Most of this work focuses on inventory management (Amorim et al., 2013), which is discussed at length in several survey papers (e.g., Chaudhary et al., 2018; Goyal & Giri, 2001; Nahmias, 1982). Here, we limit our discussion to studies that focus on distribution and/or resource allocation decisions.

Early works that consider allocation decisions for perishable products deal with the optimal assignment of perishable inventory among multiple locations with random demands (Federgruen et al., 1986; Prastacos, 1978, 1981). These studies are presented within the context of distributing blood, but rather than explicitly modeling the gradual deterioration of blood over time, a cost is incurred for any blood that is not distributed during its fixed lifetime. Most of the work related to the distribution of perishable items involves a single product type (e.g., Abouee-Mehrizi et al., 2019; Paul et al., 2019; Rong et al., 2011) whereas multiple product models with varying deterioration rates have been considered to a much lesser extent (Chaudhary et al., 2018). Examples of the latter include Lin and Chen (2003) and Li et al. (2006) who consider order decisions from suppliers and the subsequent allocation of multiple perishable products among multiple retailers. Lin and Chen (2003) aim to maximize total expected profit subject to supply and demand uncertainty, limited production capacity from the supplier, and limited receiving capacity at the retailers and Li et al. (2006) minimize supply chain costs and the lost value that occurs as a result of product deterioration.

The perishable distribution literature is based on the for-profit supply chain perspective and therefore does not consider equitable allocation as a goal. Commercial, or for-profit, supply chains commonly consider objectives such as cost minimization or profit maximization, whereas typical objectives for humanitarian supply chains are centered around equity, effectiveness, and efficiency (Beamon & Balcik, 2008). Studies related to perishable distribution have been considered within the context of production and distribution planning (Amorim et al., 2013) and also within the context of for-profit food distribution (Akkerman et al., 2010). However, we have only been able to identify one study in the long-term humanitarian operations literature that considers product perishability. Specifically, Ferreira et al. (2018) develop optimal inventory control policies for perishable items in long-term humanitarian operations (also known as continuous aid work) such as wars, droughts, and poverty. They formulate their inventory management problem as a MDP where items have a fixed shelf life and potentially expire at each decision epoch according to an Erlang distribution. However, they do not consider multiple products that deteriorate at different rates as we do in this paper, nor is equity taken into account.

2.3 | Equitable resource allocation in humanitarian operations

In the food bank operations literature, performance is typically measured in one or more of the following three dimensions: efficiency, effectiveness, and equity (Hasnain et al., 2021; Sengul Orgut, Brock, et al., 2016). In this context, efficiency generally refers to cost-related metrics, while effectiveness has to do with meeting the needs of beneficiaries; for example, the total number of beneficiaries served, the average time beneficiaries have to wait for service, or the total amount of food distributed. Equity, on the other hand, has the goal of ensuring that all beneficiaries are treated fairly, that is, they each receive an amount of food that is equally proportionate to their respective needs. A main challenge is that equity, effectiveness, and efficiency contradict with one another, creating trade-offs (Burkart et al., 2016; Gralla et al., 2014; Leclerc et al., 2012; McCoy & Lee, 2014; Park & Berenguer, 2020).

Since fairness and equity are abstract sociopolitical and subjective concepts, selection of an appropriate equity measure depends on the problem that is being considered and stakeholders' preferences (Balcik & Smilowitz, 2020; Berenguer, 2016; Leclerc et al., 2012). Marsh and Schilling (1994) provide an extensive review of equity measures that are commonly used in humanitarian operations. The food bank operations literature and Feeding America typically strive for perfectly equitable distributions. We propose strategic deviations from perfect equity through a multiperiod equity extension and also introduce a value-based approach for evaluating equity as an alternative to the traditional weight-based metrics.

3 | MODEL

We formulate the multiperiod, multiproduct perishable food distribution problem described in Section 1 as a LP model. Specifically, the distribution problem we consider consists of a food bank that receives food donations during each period of a multiperiod planning horizon and subsequently allocates these food items among multiple recipients in its service region. For the purposes of this study, it is useful to think in terms of 1-week periods since food banks usually process outgoing shipments to agencies on a weekly basis. No routing (i.e., operational planning) is considered; the LP model addresses planning at the tactical level and represents a multiperiod, multiproduct resource allocation problem. The multiperiod framework allows us to (*i*) model the deterioration of perishable food items from period to period and (*ii*) explore a multiperiod generalization of perfect equity (i.e., each county receives its fair share in each period).

The LP model highlights the trade-off between effectiveness and equity. Effectiveness typically refers to the total amount of food distributed, but because the focus of this study is perishable foods that deteriorate over time, food quality should also be accounted for in the effectiveness measure. Effectiveness is represented as the objective function of the LP model. It is calculated as the weighted sum of the amount (in pounds) of each food item distributed and its corresponding value (a number between 0 and 1 representing food quality) at the time it is distributed. Equity, on the other hand, has to do with making sure that recipients (counties) receive their fair share of food and is represented as a constraint in the LP model. Limited capacities at the counties in terms of how much food they can receive, store, and distribute are at the heart of the effectiveness/equity trade-off. To see this, consider that in the interest of preserving equity, food banks may sometimes hold on to high-value food items because a county's capacity is low. As a result, these high-value items are either distributed later at lower quality or discarded. Either way, effectiveness is negatively impacted. This paper introduces two generalizations of perfect equity to address this trade-off: (*i*) multiperiod equity where equity is achieved over multiple periods as opposed to each period and (*ii*) deviations from perfect equity where counties receive more or less than their fair shares. The multiperiod equity approach used in this study extends commonly used equity metrics in food bank operations literature and aligns with other perspectives that have been presented in the humanitarian operations literature. For example, Leclerc et al. (2012) discuss the importance of time-scope equalization when defining an equity measure. They argue that the time horizon over which to equalize should reflect the underlying operations and not be too long such that the resulting sequence of shorter time windows is characterized by unacceptably inequitable solutions.

The multiperiod, multi-item framework reveals an additional trade-off related to how items with different levels of deterioration should be prioritized for each shipment. Consider two competing approaches: (*i*) prioritizing high-value items versus (*ii*) prioritizing low-value items. If high-value items are prioritized, the distribution should perform well in terms of effectiveness because items would be distributed when they are at their highest values. However, this would cause lower value items that have not yet spoiled but will spoil in the near future to be wasted. On the other hand, prioritizing items with low remaining shelf life may reduce waste, but at the expense of overall food quality. In this regard, the multiproduct/multiperiod framework also captures the trade-off between food quality and food waste.

Letting donation instances be denoted with the indices $i \in \{1, \ldots, m\}$, counties with $j \in \{1, \ldots, n\}$, and time periods with $t \in \{1, \ldots, T\}$, the model adopts the perspective of the food bank, who decides the pounds of donation i distributed to recipient j (i.e., county j) during period t, denoted x_{ijt}. County j's per-period capacity is denoted C_j (in pounds) and per-period demand is D_j (in pounds), where we let $\Delta = \sum_j D_j$. The weight of the ith donation instance is represented as S_i (pounds) and the time period it is received by the food bank as $\tau_i \in \{1, \ldots, T\}$. This allows us to determine the value of each food donation for any week $t \geq \tau_i$. The parameter m_t is the number of food types donated to the food bank in week t, and $m = \sum_t m_t$. For example, if the food bank receives apples and oranges in week 1 and apples in week 2, then $m_1 = 2, m_2 = 1$, and $m = 3$. Thus $i = 1$ corresponds to apples received in week 1, $i = 2$ to oranges in week 1, and $i = 3$ to apples in week 2. The index i distinguishes between (*i*) different food types received in the same week because they deteriorate at different rates and (*ii*) the same food type received in different weeks. A complete list of the notation is provided in Section EC.1 of the Supporting Information.

Effectiveness and perishability

The objective function represents effectiveness in our model. It maximizes the total value-weighted pounds of food distributed over a multiperiod planning horizon: $\sum_i \sum_j \sum_t V_{i,t-\tau_i} x_{ijt}$. The notation $V_{i,t-\tau_i}$ represents the value of the ith food donation after $t - \tau_i$ periods of deterioration. To represent the decay process of each perishable food item considered later in the case study, we introduce value functions $W_{k_i} : (t - \tau_i) \mapsto V_{i,t-\tau_i}$, where $k_i \in \{1, \ldots, K\}$ is the food category that the ith donation belongs to and K is the number of said food categories. $W_{k_i}(t - \tau_i)$ has the following two properties. First, $0 \leq W_{k_i}(t - \tau_i) \leq 1$, where $W_{k_i}(t - \tau_i) = 1$ indicates that the food item is in perfect condition (no deterioration has occurred), and $W_{k_i}(t - \tau_i) = 0$ means that the maximum amount of deterioration has occurred such that the food item has no value and is no longer usable. The second property is that $W_{k_i}(t-\tau_i)$ is a decreasing function in terms of $t-\tau_i$. To vary the decay processes associated with donated food items, we assume that the value of each item i decays exponentially with deterioration rate λ_{k_i} and has the form $\exp(-\lambda_{k_i}(t-\tau_i))$, which is a common approach used in the literature (Blackburn & Scudder, 2009; Li et al., 2006).

Equity

We define e as the length of the equity window and ρ the equity deviation limit. Specifically, e represents the number of periods over which the total amount of food distributed to each county has to be equitable. The parameter ρ can be interpreted as the maximum allowable deviation from perfect equity over e periods for a given value of e. These two parameters allow equity to be controlled through the following constraint:

$$\left|\frac{\sum_i \sum_{t=e(k-1)+1}^{ke} x_{ijt}}{\sum_i \sum_j \sum_{t=e(k-1)+1}^{ke} x_{ijt}} - \frac{D_j}{\Delta}\right| \le \rho \quad \forall\, j, k = 1, \ldots, \left\lfloor \frac{T}{e} \right\rfloor. \tag{1}$$

Perfect equity, the ideal case in practice, occurs when $e = 1$ and $\rho = 0$. This means that every $e = 1$ periods, the maximum allowable deviation from perfect equity over all the counties is $\rho = 0$. In other words, all counties receive their fair share in each period. Less than perfect equity occurs when $e > 1, \rho > 0$, or both. In this case, the amount of food distributed to each county over e periods is within ρ of its fair share. Hence, constraint (1) ensures that the proportion of food received by county j over e periods relative to the amount of food distributed during those periods deviates from the proportion of demand in county j by no more than an equity deviation limit, ρ. This study explores deviations from perfect equity as an approach to addressing the equity/effectiveness trade-off and as a way to help reduce food waste. Constraint (1) can be rewritten as

$$-\rho \le \frac{\sum_i \sum_{t=e(k-1)+1}^{ke} x_{ijt}}{\sum_i \sum_j \sum_{t=e(k-1)+1}^{ke} x_{ijt}} - \frac{D_j}{\Delta} \le \rho \quad \forall\, j, k = 1, \ldots, \left\lfloor \frac{T}{e} \right\rfloor, \tag{2}$$

which can be linearized as constraints (4) and (5) in the LP model.

Supply and capacity constraints

The supply constraint states that the amount of each donation i distributed in each period t can be no more than the amount of donation i available at the beginning of period t, and the capacity constraint limits the total pounds of food a county can receive in each period to that county's per-period capacity. Additional constraints are included to ensure that no donation is distributed before it is received (logic constraints), and that the food allocation quantities are nonnegative.

We now present the LP model, referred to as the perishable food distribution model (PFDM).

PFDM:

$$\text{Maximize:} \quad \sum_i \sum_j \sum_t V_{i,t-\tau_i} x_{ijt} \quad \text{(total value)} \tag{3}$$

Subject to

$$\Delta \sum_i \sum_{t=e(k-1)+1}^{ke} x_{ijt} + (-D_j - \rho\Delta) \sum_i \sum_j \sum_{t=e(k-1)+1}^{ke} x_{ijt} \le 0$$

$$\forall\, j, k = 1, \ldots, \left\lfloor \frac{T}{e} \right\rfloor \quad \text{(equity)}, \tag{4}$$

$$-\Delta \sum_i \sum_{t=e(k-1)+1}^{ke} x_{ijt} + (D_j - \rho\Delta) \sum_i \sum_j \sum_{t=e(k-1)+1}^{ke} x_{ijt} \le 0$$

$$\forall\, j, k = 1, \ldots, \left\lfloor \frac{T}{e} \right\rfloor \quad \text{(equity)}, \tag{5}$$

$$\sum_j \sum_t x_{ijt} \le S_i \qquad \forall\, i \quad \text{(supply constraint)}, \tag{6}$$

$$\sum_i x_{ijt} \le C_j \qquad \forall\, j, t \quad \text{(capacity constraint)}, \tag{7}$$

$$\sum_j \sum_{t=1}^{\tau_i - 1} x_{ijt} = 0 \qquad \forall\, i \quad \text{(logic constraint)}, \tag{8}$$

$$x_{ijt} \ge 0 \qquad \forall\, i, j, t. \tag{9}$$

4 | CASE STUDY

In practice, Feeding America affiliated food banks strive for perfect equity with each distribution, which is difficult to achieve in practice. This paper explores the implications of that approach and proposes intentional deviations from perfect equity as an alternative. The LP model presented in Section 3 allows deviations from perfect equity through the parameters e and ρ. As such, this section examines the effects that e and ρ have on food bank performance with respect to effectiveness and equity. The specific metrics used to characterize effectiveness, equity, and the trade-off between them are as follows:

1. *Total weight of food distributed* during a multiperiod planning horizon, that is, $\sum_i \sum_j \sum_t x_{ijt}$. It is a measure of effectiveness. The benchmark for this metric is the total supply, that is, $\sum_i S_i$.
2. The *objective function value* Z^* also measures effectiveness and represents the total value of food distributed during a multiperiod planning horizon. Z^* takes both food quantity and quality into account. It is calculated as the weighted sum of the quantity of each food item distributed

and its value at the time of shipment. The benchmark for this metric is achieved if all donations are distributed in the period that they are received by the food bank.

3. *Cost of equity* for the purposes of this study is defined as the percent deviation of the optimal objective function value for given values of e and ρ ($Z^*_{e,\rho}$) from the optimal objective function value with no equity requirements ($Z^*_{\max}$). This follows the definition by Bertsimas et al. (2011). Cost of equity thus captures the effectiveness/equity trade-off and is calculated as

$$\text{Cost of equity} = \frac{Z^*_{max} - Z^*_{e,\rho}}{Z^*_{max}}.$$

The benchmark for this metric is zero (when there is no equity requirement: $Z^*_{max} = Z^*_{e,\rho}$).

4. *Waste* for the purposes of this study is defined as the percentage of food received by the food bank that is not distributed. It is a measure of effectiveness and is calculated as

$$\text{Percentage waste} = \frac{\sum_i S_i - \sum_i \sum_j \sum_t x_{ijt}}{\sum_i S_i}.$$

The benchmark for this metric is zero, which occurs when all of the supply is distributed.

5. *Average deviation of county j from its fair share*, denoted $\bar{\psi}_j$, is related to equity. Specifically, $\bar{\psi}_j$ is the average deviation of county j from its fair share over the entire planning horizon T:

$$\bar{\psi}_j = \frac{1}{T} \sum_t \left| \frac{\sum_i x_{ijt}}{\sum_i \sum_j x_{ijt}} - \frac{D_j}{\Delta} \right| \quad \forall j. \qquad (10)$$

The benchmark for this metric is FBCENC's actual distribution.

6. *Average value per pound distributed to county j*, denoted $\bar{v}_j$, may be considered both a measure of equity and effectiveness and is defined as follows:

$$\bar{v}_j = \frac{\sum_i \sum_t V_{i,t-\tau_i} x_{ijt}}{\sum_i \sum_t x_{ijt}} \quad \forall j.$$

The benchmark for this metric is $\bar{v}_j = 1$, which is achieved when all food items are distributed in the period they are received by the food bank.

The remainder of this section investigates impact of e and ρ relative to one or more of the above measures and derives managerial insights regarding the effectiveness/equity trade-off. The ensuing analysis is based on real-world data collected from FBCENC. The data and process used to estimate the parameter values for PFDM (the LP model introduced in Section 3) are relayed in Section 4.1. Section 4.2 examines FBCENC's actual shipments during a 3-month planning horizon and compares the results to the optimal shipment schedules determined by PFDM during that same period. Section 4.3 presents an in-depth analysis of the effectiveness/equity trade-off and demonstrates that by allowing only modest deviations from perfect equity, significant gains in effectiveness are possible. Section 4.4 examines how perishability and county capacities affect the effectiveness/equity trade-off. Section 4.5 proposes an equity measure that is based on value rather than weight and examines the impact this measure has on the effectiveness/equity trade-off. Section 4.6 illustrates the benefit of the multiperiod model compared to the approach of applying a single-period model on a rolling horizon basis. All experiments were conducted on a 64-bit Intel Core i7 machine with a 3.6-GHz processor and 64 GB memory and using the Python programming language. Computation times were negligible (maximum run time below 3 min per instance) and, hence, are not reported.

4.1 | Data

The data come from FBCENC's records of incoming donations and outgoing shipments during the first quarter (12 weeks) of 2018 (more than 60,000 transactions) as well as publicly available census data for 34 North Carolina counties. FBCENC handles more than 50 categories of food, so we first describe how we navigate the data in order to isolate the perishable items and estimate the model parameters m and S_i (total number of donation instances and total pounds of instance i, respectively, where $i = 1, \dots, m$). Next, we describe how the food deterioration rates λ_{k_i} are determined. Lastly, we explain how the census data and outgoing shipment records are used to determine the county demands D_j, and the county capacities C_j.

4.1.1 | Estimating food donations

FBCENC maintains detailed logs of food items received from donors as well as distribution of food to county agencies. The resulting database has 40 data fields, four of which are relevant to the purpose of estimating daily food donations for the purposes of this study. The first field is *entry type*, which can be classified as "purchase" (incoming donations) or "distribution" (outgoing shipments). Purchase entry types are linked to estimating donations, while distribution entry types play a role in estimating county demands and capacities as will be explained in Section 4.1.3. Next, the *storage requirements* column identifies four main categories of food: dry goods (51%), refrigerated food (34%), frozen food (14%), and produce (< 1%) (percentages based on the donations collected during 2017–2018 fiscal year). This case study is centered around refrigerated foods since they represent the largest category of FBCENC's perishable food items. The *product type* field describes food items with more specificity than the storage requirements field, for example, meat, dairy, grains, and snacks. This is the field that corresponds to the value functions W_{k_i} described in Section 3, where $k_i = 1, \dots, K$ and K is the number of food categories. Lastly, the *gross weight* column represents the pounds of donation i received if the entry type is "purchase" or the pounds of donation i distributed if the entry type is "distribution." For incoming donations, the gross weight field corresponds to the parameter S_i, which is the quantity of the ith donation in the refrigerated category.

Of the more than 60,000 shipping and receiving transactions that occurred during the first 12 weeks of 2018, about 19% were incoming donations and the remaining 81% were outgoing shipments. The incoming transactions included 83 refrigerated food items of 12 distinct categories. (Recall that transactions of the same food category in a given week were considered to be a single donation item.) In summary, the following parameters are used for our case study: $T = 12$, $m = 83$, and $K = 12$.

4.1.2 | Modeling perishability

We define the value function for the ith donation as $W_{k_i}(t - \tau_i) = \exp(-\lambda_{k_i}(t - \tau_i))$, which satisfies the requisite properties stated in Section 3. We obtain the exponential decay rates λ_{k_i} empirically for each of the $k_i = 1, \dots, K = 12$ food categories. The λ_{k_i} values are parameterized based on the shelf life data for various food groups presented in the Greater Pittsburgh Community Food Bank (2018) document. The shelf lives for the refrigerated food items considered in this study are provided in the Section EC.2 of the Supporting Information. FBCENC does not record the initial conditions of the food donations they receive. Therefore, we assume that each incoming food donation is in perfect condition upon arrival. Since exponential functions only approach zero asymptotically, but never actually reach zero, we assume $\min_t W_{k_i}(t - \tau_i) = 0.10$ for all k_i (i.e., food items perish when they decay to 10% of their original values). Therefore, letting s_{k_i} be the shelf life for food items in category k_i, λ_{k_i} is then calculated by solving $\exp(-s_{k_i}\lambda_{k_i}) = 0.10$, or equivalently, $\lambda_{k_i} = (1/s_{k_i})\ln(0.1)$.

4.1.3 | Estimating county demands and capacities

FBCENC uses U.S. Census Poverty Population data (United States Census Bureau, 2020) along with PPIP to estimate county demands. Specifically, let p_j denote size of the poverty population in county j according to the census data. Then the county demands (in pounds) are estimated as

$$D_j = \text{PPIP} \times p_j.$$

We estimate PPIP by referring to FBCENC's outgoing shipment data during the 2017–2018 fiscal year. In particular, letting $\bar{x}_R$ represent the average weight of refrigerated food distributed per week by FBCENC, then

$$\text{PPIP} = \frac{\bar{x}_R}{\sum_j p_j},$$

which turns out to be PPIP = 0.23 pounds/person/week for the refrigerated food category.

The county capacities C_j are also estimated based on FBCENC's outgoing shipping records. Since neither FBCENC nor county agencies determine county capacities directly, we adopt the approach presented in Sengul Orgut, Ivy, et al. (2016) and estimate C_j as the 90th percentile of weekly shipments to county j. That is, if x_{jt}^R is the amount of refrigerated food shipped to county j on week t during the 2017–2018 fiscal year, and π_j^p is the pth percentile of the set $\chi_j = \{x_{jt}^R : t = 1, \dots, 52\}$ for each county $j = 1, \dots, 34$, then $C_j = \pi_j^{90}$. Together, the county demands D_j and capacities C_j can characterize the potential for food insecurity in each county j. Specifically, the ratio of a county's capacity to its demand (CD ratio) is a measure of that county's ability to alleviate food insecurity with help from the food bank. The county with the minimum CD ratio is referred to as the *bottleneck county* (Sengul Orgut, Ivy, et al., 2016).

4.2 | Improving current policy: Total food distributed and percentage waste

This section describes FBCENC's incoming donation and outgoing shipment data from the first quarter of 2018 for items in the refrigerated food category. FBCENC's outgoing shipments during this period will serve as the benchmark scenario and a basis for comparison to results generated by PFDM. During this time, FBCENC received 4,568,146 pounds of refrigerated food donations, distributed 4,269,637 pounds of food across its 34 county service region (6.53% of its food supply was not distributed) and deviated from perfect equity by 1.79% on average (the actual quantities of food distributed to each county are shown in Section EC.3 of the Supporting Information). Note that the FBCENC data only reports donation and shipment quantity totals (in pounds) at each time period. As such, the performance metrics we consider in this section are the weight of food distributed and the percentage of food wasted as opposed to the objective function value, which requires item values.

Figure 2 shows weekly donation quantities received by FBCENC (the blue dashed line), the outgoing shipment quantities (the red solid line), and solutions by PFDM for various (e, ρ) combinations. There are several observations to be pointed out. First, the incoming donations line (blue dashed) is almost always above the outgoing shipments line (red solid), and this difference is more pronounced right after bulk donations are received (spikes). This means that the shipping policy used in practice did not ship all of the food supply during the time period considered. In fact, 93% of the food supply was shipped. The perfect equity version of PFDM (green dash-dotted line) improves upon the current policy by shipping 95% of the food supply. However, the gap between PFDM under perfect equity (green dash-dotted) and incoming donations (blue dashed) suggests a lag between when items are received and when they are

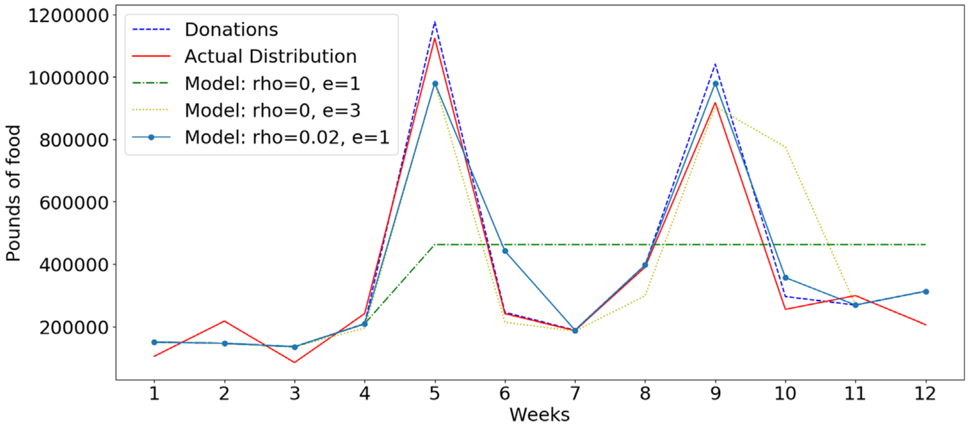


FIGURE 2 Benchmark case versus model results. [Color figure can be viewed at wileyonlinelibrary.com]

shipped. This allows food deterioration to occur which in turn results in the distribution of lower quality food and/or food waste due to spoilage. Note that the green dash-dotted line plateaus because of the bottleneck county. That is, the limited capacity of the bottleneck county relative to its demand coupled with the perfect equity requirement restricts the total amount of food shipped to all counties. Nonetheless, allowing small deviations from perfect equity with $(e, \rho) = (3, 0)$ or (1,0.02) results in the distribution of the entire food supply and completely eliminates food waste.

We also examine FBCENC's donation and shipment data during the second quarter of 2019 to see if there are any major differences in the results and insights described later in this study. Although the donation pattern during that period differs from in the original data (first quarter of 2018), the main findings and recommendations presented later in Section 5 remain the same. We refer the reader to Section EC.4 of the Supporting Information for further details.

4.3 | Effectiveness/equity trade-off

The previous section shows that an increase in the total amount of food distributed and a reduction in the percentage of food wasted are possible with only modest deviations from perfect equity. In this section, we continue exploring the benefits of deviating from perfect equity by examining the effects that e and ρ have on the objective function value, the cost of equity, and the distribution of inequities across all counties in the food bank's service area.

Objective function value and cost of equity
Figure 3 illustrates the changes in optimal objective function value Z^* and the cost of equity, respectively, for varying levels of e and ρ. Both show improvements as e and ρ increase, and both level off once a certain deviation from perfect equity is reached (e.g., $e = 4$ and $\rho = 0.01$ in this case). It is intuitive that Z^* and the cost of equity improve in e and ρ because larger values of e and ρ correspond to less restrictive equity requirements. It is also intuitive that no further improvements occur beyond some threshold because at some point, capacity becomes the more restrictive constraint upon which any further deviation from perfect equity has no effect. Lastly, changes in Z^* and the cost of equity as a function of e are more dramatic for smaller values of ρ. The reason for this is that smaller values of ρ correspond to more restrictive equity requirements. In this case, Z^* and the cost of equity are both sensitive to changes in e. On the other hand, the effect of e is not as pronounced for larger values of ρ because opportunities for improvement are more limited under the less restrictive equity conditions resulting from larger ρ values.

Analysis of county deviations from fair share
Since improvements in the objective function and the cost of equity come at the expense of inequitable distributions each week, it is important to examine these weekly inequities more closely. Are county deviations from their respective fair shares each week significant or modest? Do all counties deviate by roughly the same amount, or do some deviate more than others? To answer such questions, we calculate $\bar{\psi}_j$ for each county for all combinations of $e \in \{1, 2, 3\}$ and $\rho \in \{0.00, 0.01, 0.02\}$. Note that the solutions remain the same for $e \geq 3$ and $\rho \geq 0.02$ and hence are omitted here. The results are shown in Figure 4 where darker (lighter) red indicates larger (smaller) $\overline{\psi}_j$ values. The objective function value Z^* and the percentage of food waste are also reported for each (e, ρ) combination.

Several managerial insights emerge from Figure 4. First, county deviations from their fair shares are relatively modest for most of the cases considered—less than 9% for all counties except when $e = 3$, in which case only one county deviates more than 9%. In fact, the deviations for 31 of the 34 counties are between 1% and 6%. This finding also suggests that only a few counties deviate from their fair shares on a weekly basis in a significant way—the counties labeled 1, 2, and 3 in Figure 4. The area labeled (1) is Wake county. It has the largest poverty population in FBCENC's service region. Areas (2) and (3) represent Durham and Pitt counties, respectively, and are also densely populated areas. As such, allowing these counties to deviate from their fair shares, even

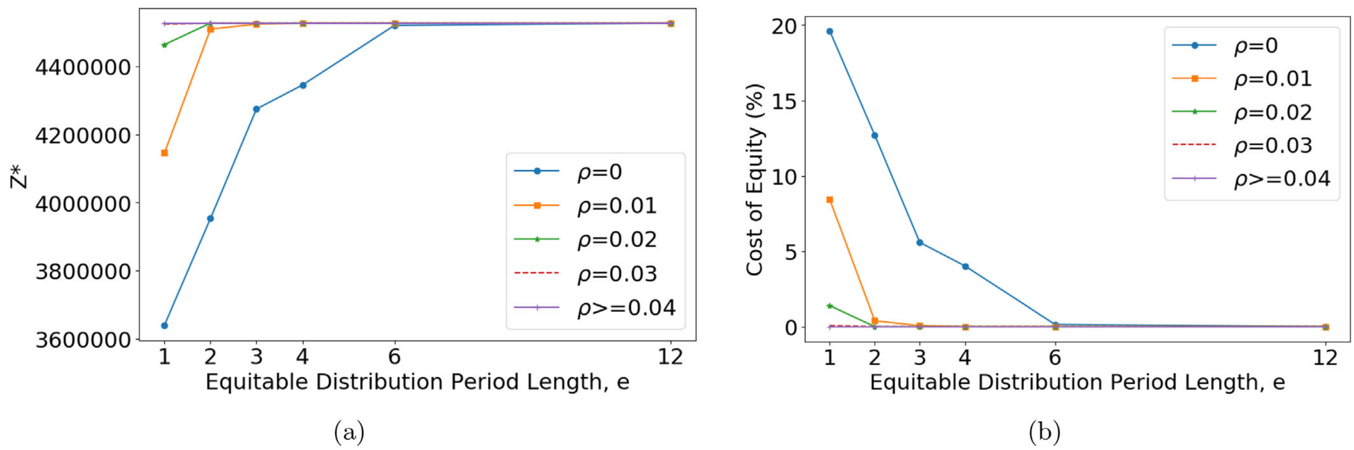


FIGURE 3 Change in (a) Z^* and (b) cost of equity for varying e and ρ. [Color figure can be viewed at wileyonlinelibrary.com]

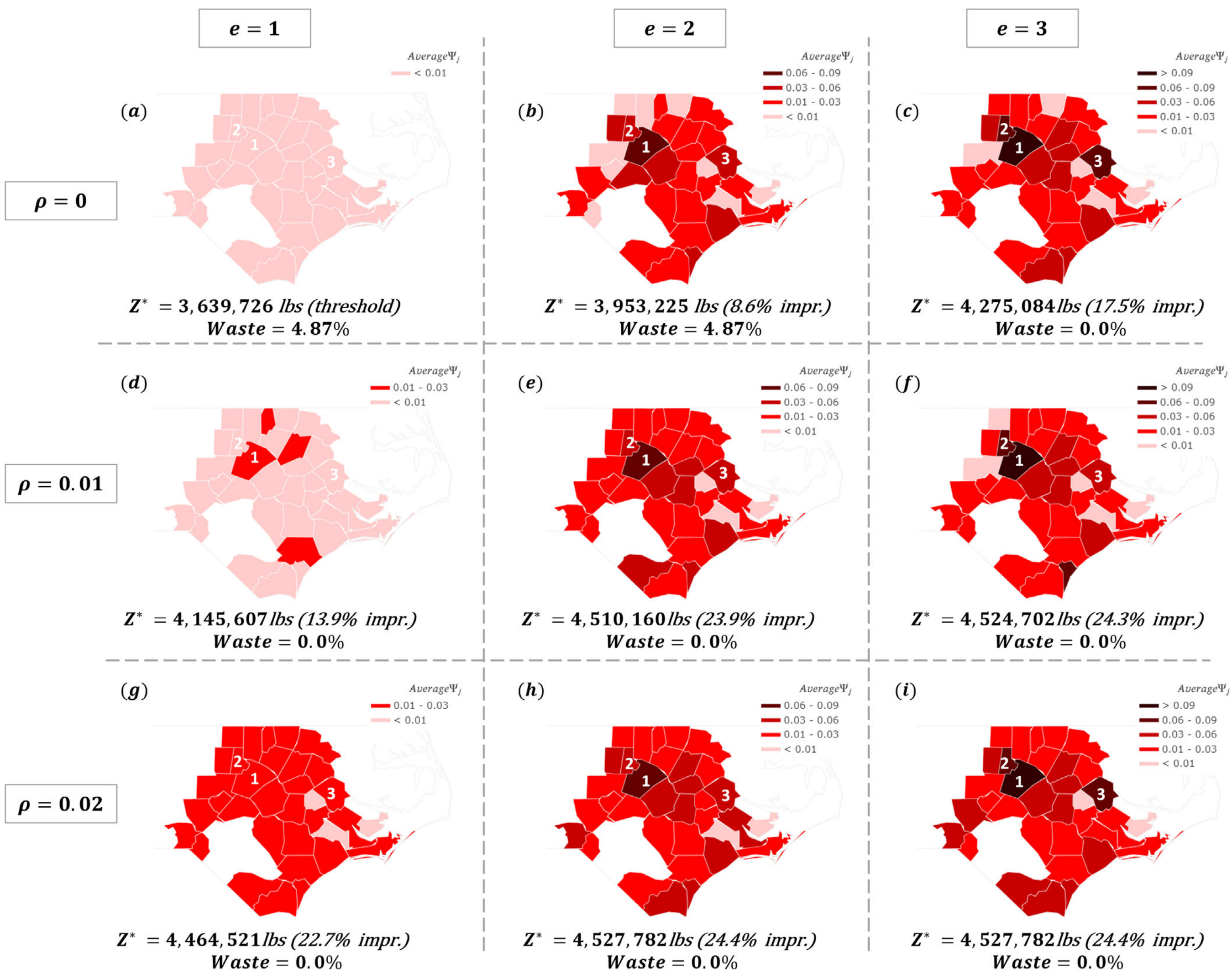


FIGURE 4 $\bar{\psi}_j$, Z^*, % improvement in Z^* and % waste for varying e and ρ. (1) Wake; (2) Durham, (3) Pitt. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Impact of e and ρ on $\bar{\psi}_j$ and cost of equity. Last row: equity deviation of FBCENC's distribution.

		$\bar{\psi}_j$				
ρ	e	Average	St. Dev.	Min.	Max.	Cost of equity (%)
0	1	0.00%	0.00%	0.00%	0.00%	19.61%
	2	2.04%	1.51%	0.27%	6.47%	12.69%
	3	2.54%	1.98%	0.30%	9.51%	5.58%
	4	2.81%	2.15%	0.34%	11.55%	4.02%
	6	2.82%	2.04%	0.32%	8.30%	0.15%
	12	2.90%	2.22%	0.41%	11.17%	0.00%
0.01	1	0.87%	0.12%	0.54%	1.00%	8.44%
	2	2.33%	1.49%	0.82%	6.61%	0.39%
	3	2.77%	2.43%	0.74%	12.97%	0.07%
	4	2.96%	2.34%	0.63%	12.71%	0.00%
	6	3.06%	2.56%	0.35%	11.98%	0.00%
	12	3.23%	2.36%	0.60%	10.38%	0.00%
0.02	1	1.61%	0.31%	0.86%	2.00%	1.40%
	2	2.70%	1.45%	0.50%	6.90%	0.00%
	3	2.96%	1.97%	0.80%	10.25%	0.00%
	4	3.10%	2.52%	0.70%	13.51%	0.00%
	6	3.37%	2.07%	1.07%	12.14%	0.00%
	12	3.35%	2.59%	0.63%	14.37%	0.00%
FBCENC actual		1.79%	1.27%	0.75%	7.66%	

by small amounts, results in meaningful improvements to Z^* and reductions in the amount of food waste.

Figure 4 also shows that improvements in Z^* and reductions in waste are accomplished more equitably when ρ is increased compared to when e is increased. For example, increasing ρ from 0 to 0.01 provides a solution that is better in terms of both equity and effectiveness compared to the solution obtained by increasing e from 1 to 2. When ρ is increased to 0.01, Z^* improves by almost 14% compared to an 8.6% improvement when e is increased to 2. Moreover, that same increase in ρ results in 0% waste whereas the increase in e produces nearly 5% waste. In fact, $\rho = 0.02$ along with the nominal $e = 1$ value shown in Figure 4g arguably represents the most desirable scenario. Here, all but three county deviation percentages are in the 1–3% range, and the other three counties deviate less than 1%. No waste is produced, and Z^* improves by almost 23%—not quite the 24% improvement reported in Figure 4h,i, but far more equitable.

To further analyze county deviations from their fair shares, Table 1 shows summary statistics for the $\bar{\psi}_j$ values as well as the cost of equity percentages for $\rho \in \{0, 0.01, 0.02\}$ and $e \in \{1, 2, 3, 4, 6, 12\}$. There are several observations from Table 1. First, the marginal benefit of increasing e diminishes as e increases, and this is more pronounced for low values of ρ. For example, when $\rho = 0$, the change in cost of equity from $e = 1$ to $e = 2$ is almost 7% whereas the change is only 0.15% when e is increased from 6 to 12. This shows that the objective is sensitive to changes in e when the equity deviation ρ is small, which aligns with our discussion above. However, the marginal change in $\bar{\psi}_j$ also diminishes when e gets larger, which is fortuitous because it shows that even if a food bank chooses a large equity window, the average weekly equity deviations remain small (less than 3% when $\rho = 0$). It is also worth mentioning that the best case scenario for effectiveness (cost of equity = 0) can be achieved in different ways, by increasing e, ρ, or both. However, increasing ρ seems to provide higher benefit as it results in smaller $\bar{\psi}_j$ values while achieving the same objective (e.g., $\rho = 0$ and $e = 12$ vs. $\rho = 0.02$ and $e = 2$).

Finally, although in this paper, we examine the cost of equity, another interesting way to examine the results would be in terms of *the cost of effectiveness* defined as the minimum average $\bar{\psi}_j$ value achieved subject to a limit on the undistributed food supply (waste). Examining Table 1 and Figure 4, the cost of effectiveness for a zero waste solution would be 0.87%, achieved when $\rho = 0.01$ and $e = 1$. This reaffirms our main insight that significant improvements in effectiveness can be achieved with small and controlled deviations from equity.

In summary, the findings in this section illustrate that significant improvements in the quantity and quality of food distributed along with reductions in food waste are possible if modest deviations from the perfect equity requirement are considered.

Comparison to the benchmark case

The last row of Table 1 shows summary statistics for the $\bar{\psi}_j$ values that correspond to FBCENC's outgoing shipments during the first quarter of 2018 ($\bar{\psi}_j$ values for all counties are provided in Section EC.3 of the Supporting Information). Overall, an average $\bar{\psi}_j$ value of 1.79% shows that FBCENC's shipments during this period performed very well in terms of equity. However, it also shows that even though FBCENC strives for perfect equity with each shipment, perfect equity was actually not achieved (the average $\bar{\psi}_j$ value would be zero if it were). This finding suggests the existence of some potentially unavoidable *natural level of inequity* that occurs in practice.

Figure 5 shows that there are values of e and ρ where PFDM produces solutions that dominate the solution that FBCENC used in practice. In other words, PFDM found solutions that are more equitable and produce less waste than FBCENC's solution for appropriately chosen values of e and ρ. The arrow in Figure 5 points in the direction of improved solutions—smaller average $\bar{\psi}_j$ values (more equitable) and larger percentages of food distributed (less waste). Thus, any solution that is both below and to the right of FBCENC's actual solution dominates the FBCENC solution. There are three such solutions: $(e, \rho) = (1, 0), (1, 0.01)$, and (1,0.02).

Figure 6 illustrates the improvement of PFDM compared to FBCENC's shipments in practice. FBCENC's distribution is the leftmost map and PFDM's solutions with $(e, \rho) = (1, 0), (1, 0.01)$, and (1,0.02) are the next three maps from

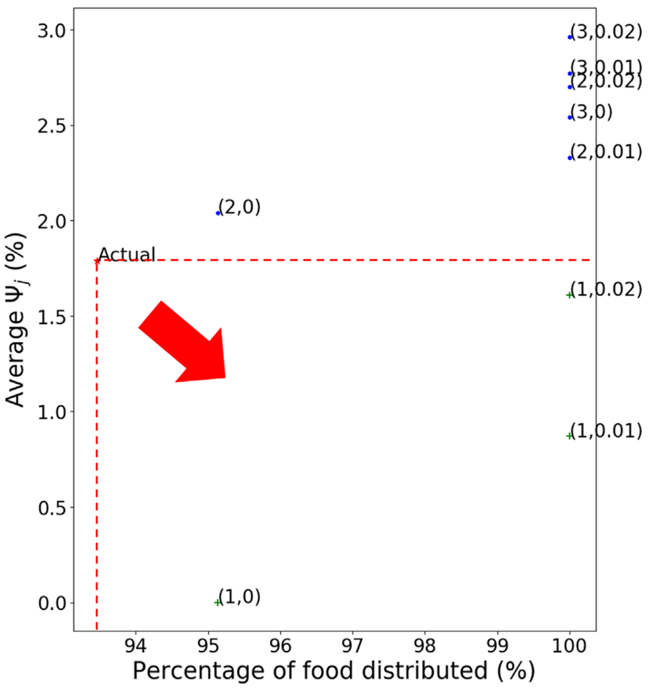


FIGURE 5 $\overline{\psi_j}$ versus percent food distributed for PFDM with various (e, ρ) values. "Actual" = FBCENC distribution. [Color figure can be viewed at wileyonlinelibrary.com]

left to right. These maps indicate that PFDM's solutions are more equitable and produce less waste than FBCENC's solution. It is also worth mentioning that FBCENC's solution is comparable to PFDM's solution with $e = 3$ (last column of Figure 4) with respect to equity (achieved $\overline{\psi_j}$ values). However, those PFDM solutions reduce waste from 6.5% to 0% when compared to FBCENC's solution.

Over- and underserved counties

The color-coded regions in Figures 4 and 6 represent the average amount per week that each county deviates from its fair share during the planning horizon (i.e., $\overline{\psi_j}$ for each county j). Although these figures give a sense of how inequities are distributed across counties, they do not indicate the directions of these equity deviations. To extend our analysis such that over- and underserved counties can be determined, we recalculate each county's deviation based on the total amount of food distributed over the 12-week horizon as follows: $\frac{\sum_t \sum_i x_{ijt}}{\sum_t \sum_i \sum_j x_{ijt}} - \frac{D_j}{\Delta}$ for all j. Figure 7 shows how each county fares relative to this metric; FBCENC's actual distribution on the left and PFDM with $\rho = 0.02$ and $e = 1$ on the right (this PFDM solution performed well for the absolute deviation case; see Figure 4). Counties shaded blue are overserved, and those shaded orange are underserved. The darker (lighter) the shade of blue or orange, the more (less) that county deviates from its fair share.

Figure 7 demonstrates that PFDM improves upon the distribution that FBCENC implemented in practice with respect to the directional equity deviation metric described above. To see this, observe that the PFDM solution reduces the range of deviations from [−1.8%, 4.7%] (FBCENC's solution) to [−1.6%, 1.8%]. Figure 7 also shows that the most over- and underserved counties are similar under both the FBCENC and PFDM distributions. Wake (1) is the most overserved county in the FBCENC distribution (4.7%) and PFDM's second most overserved (1.3%), while Nash (2) is the second most overserved for FBENC (3%) and fourth under PFDM (1.1%). One of the reasons Wake county is overserved may be attributed to FBCENC's hub being located there, which makes it easier to serve that area. However, the PFDM solution may overserve Wake for a different reason. Wake county has the largest demand in the service region, so even a small deviation from equity could significantly increase the total amount of food distributed thereby increasing effectiveness. Another consideration is Wake county's large CD ratio. Specifically, Wake county's CD ratio is the 96 percentile among all the counties, which may also explain why this county is overserved in the PFDM solution. This observation makes Brunswick county an interesting case. Brunswick (3) received their fair share in the FBCENC distribution (0.0% deviation), but is the most overserved county in the PFDM distribution (1.8%). Brunswick county's CD ratio is the 88 percentile, which also supports that counties with large CD ratios will likely be overserved. The insight here is that food banks should consider slightly overserving capacity-rich counties in order to achieve balance in equity and effectiveness.

There is a bit more alignment in how the FBCENC and PFDM distributions affect the service region's most underserved counties. Specifically, Pitt (4) and Harnett (5) are the most underserved counties in both solutions. Moreover, the equity deviations are similar: Pitt and Harnett both deviate −1.8% in the FBCENC distribution, and their deviations are −1.6% and −1.5%, respectively, for the PFDM distribution. Low CD ratios may be the reason these counties are the most underserved just as the most overserved counties have high CD ratios. The CD ratios for Pitt and Harnett counties are among the lowest with Pitt being the fourth lowest (ninth percentile) and Harnett the lowest overall. Therefore, in order to improve service to the most underserved counties, FBCENC should aim to increase capacity in those areas.

4.4 | Impact of perishability and capacity on cost of equity

This section examines the impact of food deterioration rates and county capacities on the cost of equity. The nominal deterioration rates $\boldsymbol{\lambda} = (\lambda_1, \ldots, \lambda_K)$ for all 12 food categories considered in this study are computed as described in Section 4.1.2, while Section 4.1.3 explains how the county capacities $\mathbf{C} = (C_1, \ldots, C_n)$ are calculated. To determine the impact of deterioration and county capacities, we consider three levels of each resulting in a total of nine scenarios. The three levels of deterioration are slow, nominal, and fast, and the three levels of capacity are low, nominal, and high. Recall from Section 3 that deterioration is represented as

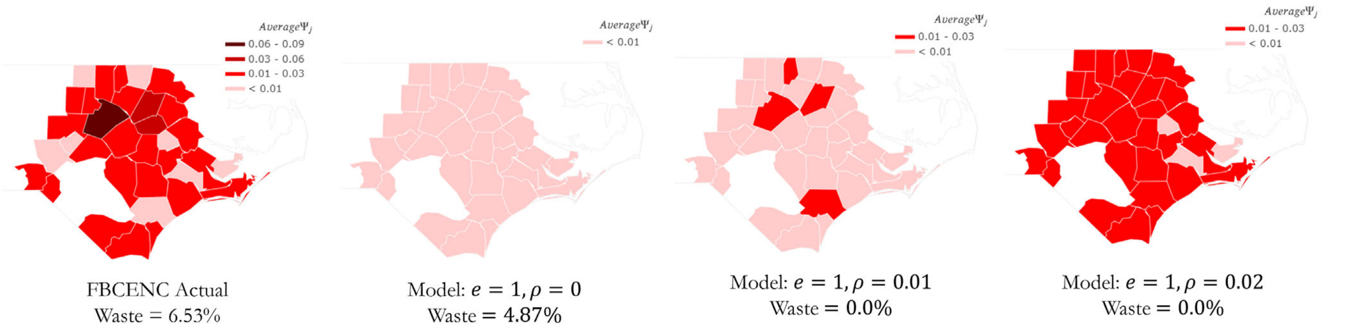


FIGURE 6 Comparison of actual distribution to dominating results from the model. [Color figure can be viewed at wileyonlinelibrary.com]

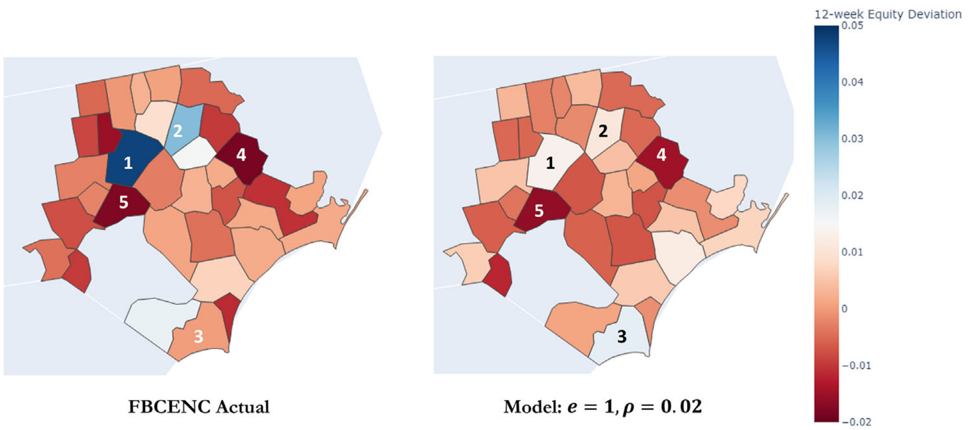


FIGURE 7 Equity deviations for each county over 12 weeks for (*i*) actual distribution by FBCENC (left side) and (*ii*) PFDM solutions for $\rho = 0.02, e = 1$; (1) Wake, (2) Nash, (3) Brunswick, (4) Pitt, and (5) Harnett. [Color figure can be viewed at wileyonlinelibrary.com]

an exponential decay function of the form $\exp(-\lambda_{k_i} t)$. Thus, larger values of $\boldsymbol{\lambda}$ indicate faster rates of deterioration. With this in mind, we represent slow deterioration as one-third of the nominal deterioration, that is, $\boldsymbol{\lambda}/3$. Similarly, the fast deterioration scenario is $3\boldsymbol{\lambda}$; low capacity is $\mathbf{C}/3$; and high capacity is $3\mathbf{C}$. Results are shown in Figure 8.

Several insights can be derived from Figure 8. The most obvious one is that cost of equity (vertical axis) decreases (or stays the same) as ρ (horizontal axis) increases. This finding agrees with intuition. The more we deviate from perfect equity towards a solution that does not consider equity at all (i.e., as ρ increases), the smaller the loss in effectiveness. To clarify, recall from the beginning of Section 4 that the cost of equity is the percent deviation of $Z^*_{e,\rho}$ (the objective function value associated with given values of e and ρ) from $Z^*_{\max}$ (the best possible objective function value in which there are no equity requirements). Thus $Z^*_{e,\rho}$ approaches $Z^*_{\max}$ as ρ increases, which makes sense because if ρ were to be increased until $Z^*_{e,\rho} = Z^*_{\max}$, then the cost of equity would be 0%. Similarly, Figure 8 shows that the cost of equity decreases when county capacities increase. This can be deduced by observing the range of the cost of equity values on the vertical axis in each row of Figure 8. This result is also intuitive—the more capacity the counties have, the easier it will be to satisfy equity requirements. Thus, there is less opportunity to improve equity and the cost of equity under high-capacity scenarios. Analogous arguments apply to the effects of increasing e.

Figure 8 also reveals insights related to the impact that deterioration rates have at different capacity levels. In the first row of Figure 8 which corresponds to the "low-capacity" scenario, the cost of equity decreases as food deterioration rates increase from slow to nominal to fast (the plotted values on the vertical axis are highest under the slow deterioration scenario and get progressively lower for the nominal and fast deterioration scenarios). The opposite occurs for the "nominal capacity" and "high-capacity" scenarios, that is, the cost of equity increases as deterioration rates increase. To explain this seemingly contradictory result, first consider that faster deterioration rates generally make it more difficult for the food bank to distribute food items prior to their expiry dates. Also consider that under higher capacity scenarios, the equity requirements are more restrictive than the capacity limitations. In this case, the opportunity to improve upon effectiveness by relaxing equity increases as food deterioration rates increase. This means that the cost of equity increases when food deteriorates faster and sufficient capacity is available (nominal capacity and high capacity rows of

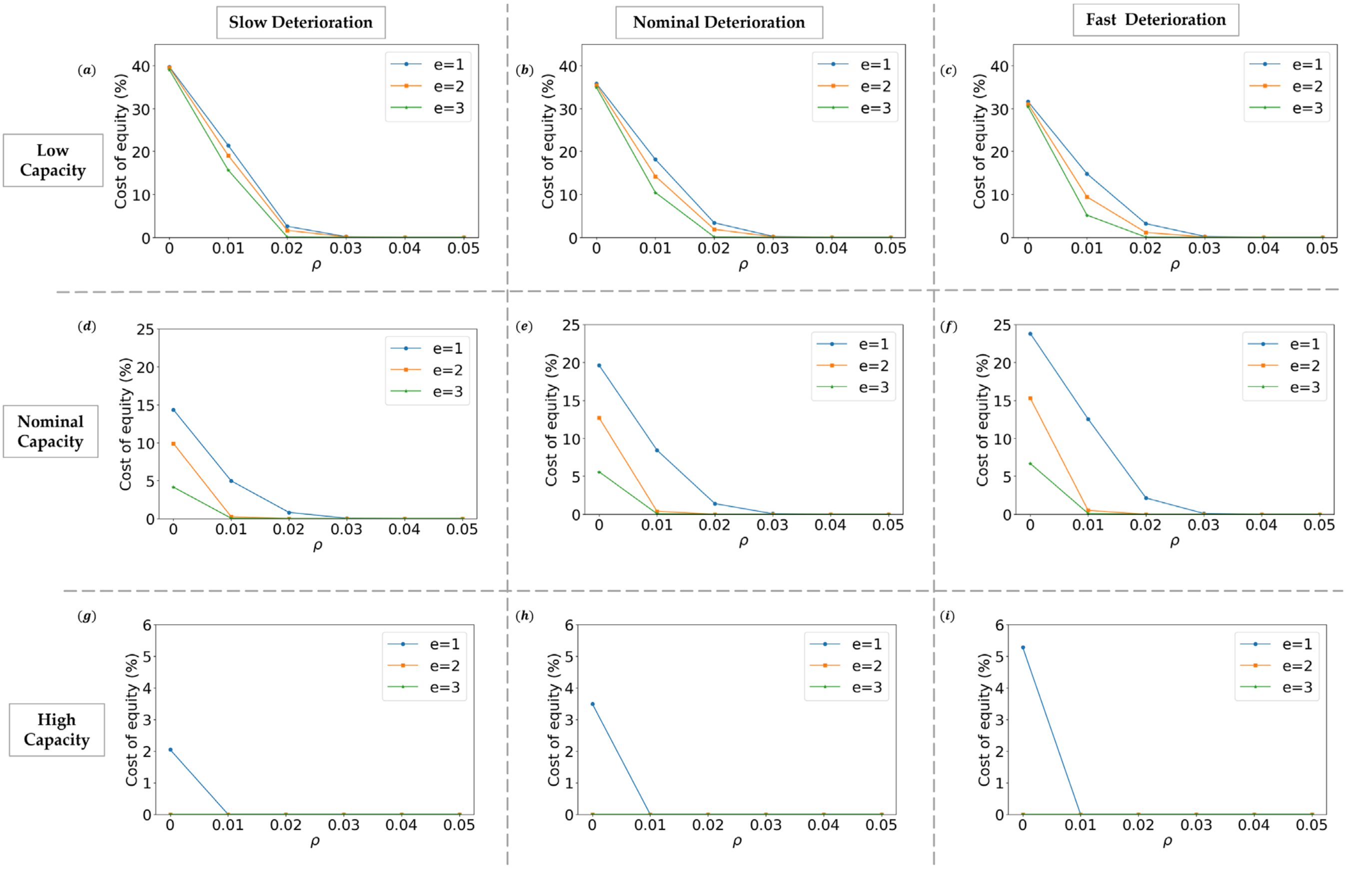


FIGURE 8 Cost of equity (%) for varying λ, capacity, e, and ρ. [Color figure can be viewed at wileyonlinelibrary.com]

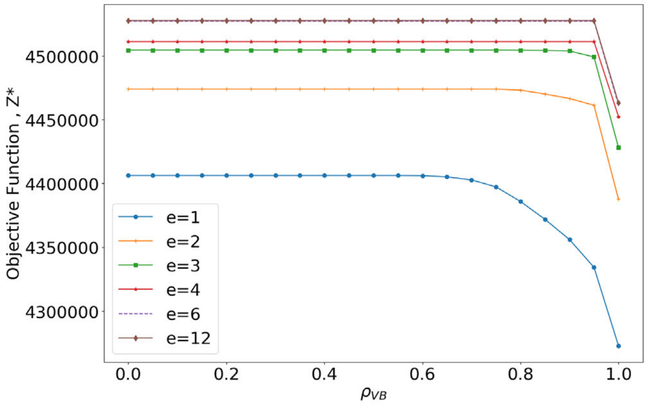
Figure 8). For lower capacity scenarios where the capacity constraints are more restrictive than the equity constraints, improvements in effectiveness cannot be achieved by relaxing equity. As such, the impact that relaxing equity can have diminishes as deterioration rates increase. In other words, the cost of equity decreases as food deteriorates faster in the absence of sufficient county capacities as shown in the low capacity row of Figure 8. Lastly, it is worth mentioning that when capacity is very high, food deterioration rates generally have minimal impact because the majority of food items can be shipped immediately when received by the food bank. This explains why the cost of equity is zero in the high-capacity scenario, except under the most restrictive equity requirements with $e = 1$ and $\rho = 0$.

In summary, the effect that increasing food deterioration rates has on the cost of equity depends on county capacities. When county capacities are low, the cost of equity decreases as deterioration rates increase because relaxing equity does little to facilitate shipping items earlier. In this case, it would be more advantageous to increase capacity than to relax equity to improve upon effectiveness. However, under higher capacity scenarios, relaxing equity can improve effectiveness which is why the cost of equity increases as food items deteriorate faster when sufficient capacity is available.

4.5 | Equity on the value of food

This section considers an alternative to the equity measure used in practice, which is represented as Constraints (4) and (5) of PFDM in Section 3. These constraints ensure an equitable distribution among beneficiaries based on the amount of food they receive. However when it comes to perishable food items, one may argue that equity should also take food quality into account. For example, if two counties receive the same amount of food where one county receives all fresh food and the other receives food that is nearly expired, is the distribution truly equitable? Motivated by scenarios like this, we formulate an equity measure that takes food quality into account. This proposed equity metric is represented as an additional constraint of PFDM rather than as a replacement of the current equity constraints (4) and (5). This is because quantity still matters, that is, people require at least a certain amount of food to survive.

To distinguish between the traditional equity metric and the new one considered in this section, we refer to the former as *weight-based equity* (*WB*) and the latter as *value-based equity* (*VB*). Similar to the WB equity constraints, we introduce a constant $\rho_{\mathrm{VB}} \in [0, 1]$ such that the average value per pound of food delivered to each county over e periods is greater than equal to the constant ρ_{VB}. Mathematically, the VB equity



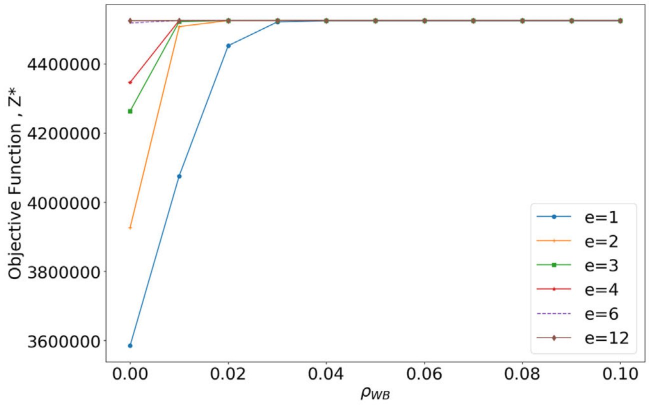


FIGURE 9 The change in Z^* for varying e and (a) ρ_{VB} and (b) ρ_{WB}. [Color figure can be viewed at wileyonlinelibrary.com]

constraint can be expressed as

$$\frac{\sum_i \sum_{t=e(k-1)+1}^{ke} V_{i,t-\tau_i} x_{ijt}}{\sum_i \sum_{t=e(k-1)+1}^{ke} x_{ijt}} \geq \rho_{\text{VB}} \quad \forall j, k = 1, \ldots, \left\lfloor \frac{T}{e} \right\rfloor, \tag{11}$$

which when linearized becomes

$$\sum_i \sum_{t=e(k-1)+1}^{ke} V_{i,t-\tau_i} x_{ijt} - \rho_{\text{VB}} \sum_i \sum_{t=e(k-1)+1}^{ke} x_{ijt} \geq 0, \quad \forall j, k = 1, \ldots, \left\lfloor \frac{T}{e} \right\rfloor. \tag{12}$$

Therefore this subsection considers PFDM with the addition of constraint (12).

VB equity represents a new way for food banks to measure equity that is based on the value, or quality, of food distributed to their service regions. Perfect VB equity is accomplished by setting $\rho_{\text{VB}} = 1$, which means all counties receive food of the highest quality with no deterioration whatsoever. At the other extreme, setting $\rho_{\text{VB}} = 0$ is equivalent to eliminating this constraint completely since it enforces no lower bound on the value of food received by the counties. Note that this interpretation is the opposite of the parameter ρ (denoted ρ_{WB} in this subsection) associated with the traditional equity measure (WB equity). Recall that $\rho = \rho_{\text{WB}} = 0$ in constraints (4) and (5) of PFDM corresponds to perfect WB equity and $\rho_{\text{WB}} = 1$ effectively eliminates WB equity as a constraint.

We consider the effectiveness/equity trade-off by examining the effects of $\rho_{\text{VB}}, \rho_{\text{WB}}$, and e on several of the metrics described at the beginning of Section 4. These parameters represent the three strategies that food banks can use to proactively deviate from perfect equity in order to improve effectiveness. We vary ρ_{WB} in [0,1] with increments of 0.05 and use the same settings as Section 4.3 for the other parameters. Figure 9 shows how these parameters affect the average optimal objective function value Z^*.

In Figure 9a, we see that Z^* either worsens or stays the same as ρ_{VB} increases, while Z^* improves (or stays the same) as ρ_{WB} increases in Figure 9b. These findings are expected: increasing ρ_{VB} corresponds to more strict equity requirements on the quality of food that can be distributed while decreasing ρ_{WB} tightens quantity-based equity restrictions (the latter parallels results from Section 4.3). We also observe that Z^* converges for a given value of e for $\rho_{\text{VB}} \leq 0.5$ in Figure 9a and $\rho_{\text{WB}} \geq 0.04$ in Figure 9b. Thus, no gains in effectiveness are possible once VB or WB equity is relaxed beyond a certain point. However, it is interesting to note that Z^* converges to the same value for all values of e as ρ_{WB} increases in Figure 9b, but for each value of e considered in Figure 9a, Z^* stabilizes to different values as ρ_{VB} decreases. This suggests that e has a greater impact on improving effectiveness when VB equity is progressively relaxed compared to when WB equity is relaxed. Figure 9 also indicates that WB equity is more limiting than VB equity, which makes VB equity easier to achieve once WB equity is relaxed beyond a certain threshold. This can be inferred based on the smaller Z^* values along the y-axis in Figure 9b compared to the Z^* values in Figure 9a.

We now turn our attention to how the parameters $(e, \rho_{\text{VB}}, \rho_{\text{WB}})$ affect equity by considering the metrics $\bar{\psi}_j$ and $\bar{v}_j$ defined at the beginning of Section 4. Figure 10a is a scatter plot of $\bar{v}_j$ versus the average of the $\bar{\psi}_j$ values over all counties. It only shows solutions that distribute the entire food supply (2216 instances) for consistency in order to accurately reflect the trade-off. In Figure 10a, a solution X dominates a solution Y if X is above and to the left of Y. This is because larger $\bar{v}_j$ means a larger average value per pound distributed and smaller average $\bar{\psi}_j$ indicates smaller equity deviations. Figure 10b shows the nondominated solutions (i.e., the efficient frontier) from the scatter plot. The two solutions $(e, \rho_{\text{VB}}, \rho_{\text{WB}}) = (1, 0.75, 0.02)$ and (1,0.85,0.02) (shown as stars in Figure 10b) provide good options as they achieve an average value per pound of about 0.98 across the counties with a WB equity deviation of only 1.6%. There are other options where the average value per

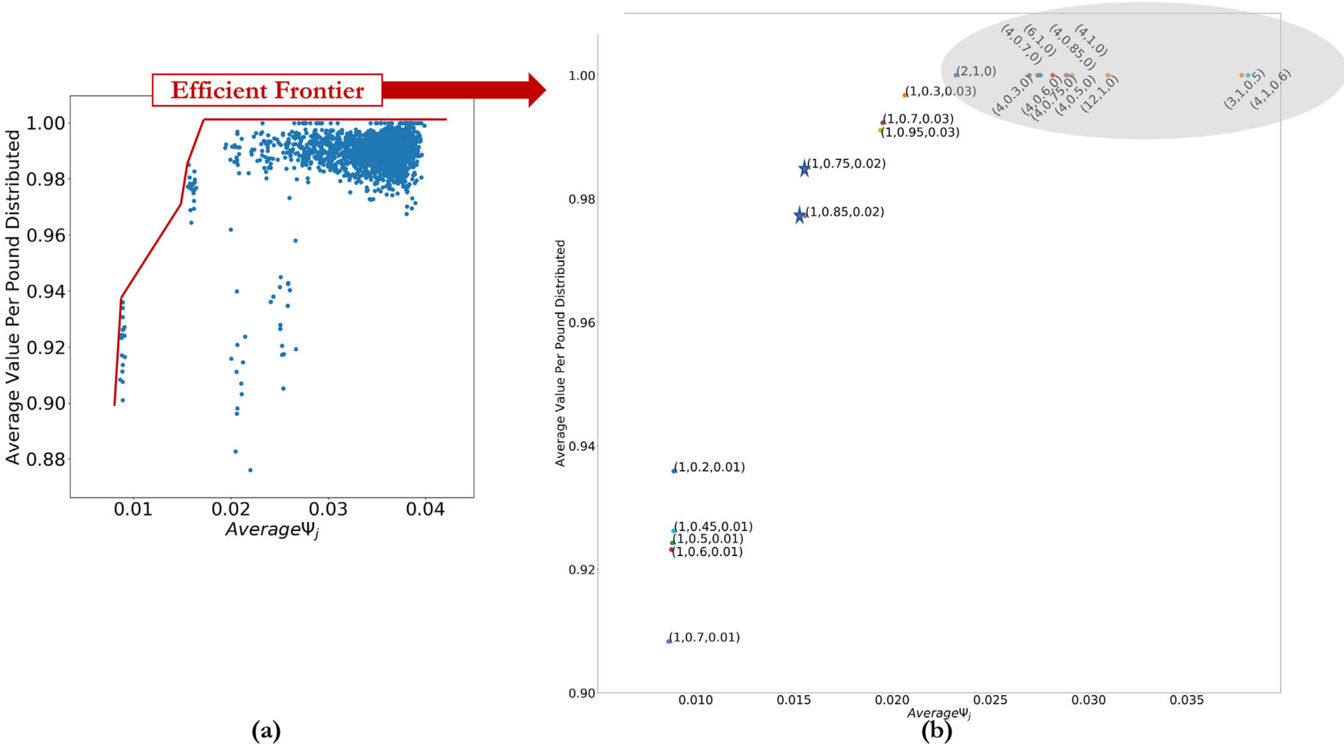


FIGURE 10 Average value per pound ($\bar{v}_j$) versus the average $\bar{\psi}_j$ for (a) all solutions with zero waste and (b) the efficient frontier. The labels in parentheses represent (e, ρ_{VB}, ρ_{WB}). [Color figure can be viewed at wileyonlinelibrary.com]

pound is 1 (in the gray-shaded area), but these result in worse WB equity deviations (greater than 2%).

Figure 10 reveals the existence of an additional trade-off that has not been considered previously: the trade-off between WB and VB equity. In particular, improvements in WB equity (lower $\bar{\psi}_j$) come at the expense of a lower average value per pound distributed (lower $\bar{v}_j$). To better appreciate this trade-off, consider the extreme cases. In order to have perfect WB equity (and zero waste), deviations in food quality are inevitable. On the other hand, perfect VB equity requires shipping each food item to the counties during the period it is received by the food bank. To maintain zero waste in this scenario, inequities in the quantity of food received by the counties will occur due to capacity restrictions. Food banks can choose values for (e, ρ_{VB}, ρ_{WB}) that balance this trade-off according to their preferences.

4.6 | Impact of planning horizon on Z^*

This section describes the performance improvements that are possible as a result of our multiperiod modeling framework. Our basis for comparison is a series of single-period models solved on a rolling horizon basis during a multiperiod planning horizon. The length of the planning horizon is 12 weeks and is based on the dataset described in Section 4.1. We examine the impact that the length of the planning horizon has on performance improvements.

To characterize the impact of planning horizon length, horizons of length T are considered where $T \in \{1, 2, 4, 6, 12\}$. More specifically, six scenarios of PFDM are solved, one for each $T \in \{1, 2, 4, 6, 12\}$. However, for all $T \neq 12$, PFDM is solved on a rolling horizon. For example, when $T = 2$, six instances are solved sequentially. The first instance is solved considering only the donations received in periods $t = 1, 2$. Any undistributed food items from the first instance are carried over as inventory into period $t = 3$. Then the second instance is solved with the beginning inventory from period 3 and any donations received during periods $t = 3, 4$. This process continues until each of the six problem instances is solved, and all 12 periods of the planning horizon have been covered. The overall objective function for the 12-period horizon is calculated as the sum of the six objective function values from the six problem instances. This explanation is easily adapted for $T = 1, 4$, and 6.

Results are reported in Table 2. The benchmark is $T = 1$ and $e = 1$ for $\rho \in \{0.00, 0.01, 0.02\}$ (second column). Performance improvements in subsequent columns are relative to this benchmark. The results show that the multiperiod framework performs up to 25% better than the approach of solving a single-period model on a rolling horizon. Further, the benefit of the multiperiod model with respect to the overall value of food distributed improves as the length of the planning horizon increases. However, the benefits are much smaller if deviations from perfect equity of not more than ρ percent

TABLE 2 Impact of changing the planning horizon T on objective function value, Z^*.

	Z^*	% Improvement							
	$T = 1$	$T = 2$		$T = 4$		$T = 6$		$T = 12$	
ρ	$e = 1$	$e = 1$	$e = 2$	$e = 1$	$e = 4$	$e = 1$	$e = 6$	$e = 1$	$e = 12$
0.00	3,601,233	0.42%	6.06%	1.07%	20.67%	0.92%	25.54%	1.07%	25.73%
0.01	4,111,597	0.52%	9.57%	0.83%	10.12%	0.70%	10.12%	0.83%	10.12%
0.02	4,434,401	0.68%	2.11%	0.68%	2.11%	0.68%	2.11%	0.68%	2.11%

are allowed every e periods, which is consistent with findings reported in earlier sections. In particular, the benefit of relaxing equity by allowing longer equity windows e diminishes as ρ increases, and that increasing ρ is a more effective approach to improving effectiveness while preserving equity compared to the approach of increasing e. These findings have been verified for every possible e and $T \in \{1, 2, 4, 6, 12\}$ (see Section EC.5 of the Supporting Information).

5 | DISCUSSION AND MANAGERIAL INSIGHTS

Food banks strive to distribute food donations in ways that minimize waste (effectiveness) and achieve equity in their service regions. Unfortunately, capacity restrictions that exist in practice prevent them from achieving both objectives simultaneously. Our case study reveals that achieving equity and effectiveness is particularly challenging for food banks when (*i*) donations are perishable, (*ii*) donations are received in bulk, and (*iii*) distribution capacities are prohibitive. Capacity limitations and equity requirements make it difficult for food banks to distribute food quickly, which results in food deterioration or even food waste if the food items are highly perishable. However, the good news is that food banks can use our model to plan small and controlled deviations from perfect equity that will enable them to distribute their entire food supply with less food deterioration.

In practice, food banks often deviate from perfect equity by retroactively redistributing leftover food that might have otherwise been wasted. This study proposes an alternative to current practice where the food bank takes a proactive approach to managing the equity/effectiveness trade-off by allowing strategic deviations from perfect equity in the original distribution plan. We present two options for deviating from perfect equity: (*i*) allowing equity to be achieved across multiple periods and (*ii*) allowing a maximum deviation from perfect equity with each period. Although both options improve effectiveness (i.e., reduce waste), option (*ii*) is more effective in terms of both the quality and quantity of food distributed compared to option (*i*). Also, it is worth mentioning that when equity deviations are allowed each period, only a few counties actually deviate from receiving their fair share. However, if food banks prefer the longer equity window approach, they should note that the marginal benefit diminishes as the length of the equity window increases, especially if little or no equity deviations are allowed each period. Our findings also suggest that counties with larger capacity/demand ratios (CD ratios) tend to be overserved while those with smaller CD ratios are likely to be underserved. Therefore, to offset some of equity loss that occurs when setting target equity deviations each period, food banks should prioritize investments that increase the refrigerated food capacity of counties in their service regions with smaller CD ratios. Example investments include recruiting new agencies in low CD ratio counties or deploying mobile pantries to those areas. In general, our results suggest that capacity limitations and rapid food deterioration are impediments to successful management of the equity/effectiveness trade-off for food banks.

Traditional notions of equity in practice and in the food bank operations literature are based solely on the quantity of food distributed. However, for products such as refrigerated food items that deteriorate over time, an additional dimension of equity warrants consideration: food quality. We explore an approach where the distribution takes both quantity and quality into account with respect to equity and examines the trade-off between them. It turns out that in the majority of cases, quantity-based equity is more difficult to achieve than quality-based equity. As such, food banks can expect large quality-based equity improvements with modest equity deviation targets when large quantity-based equity deviations are permitted (or relaxed entirely). On the other hand, larger target deviations from perfect equity are necessary in order to realize meaningful improvements in quantity-based equity whenever quality-based equity targets are minimal or nonexistent. In any case, our model still provides solutions that achieve both forms of equity while minimizing waste. Lastly, our findings suggest that food banks should consider developing distribution plans that span several periods (weeks) at a time as opposed to 1-week plans each week. The multiperiod planning approach can be up to 25% better than week-to-week planning according to our case study. This is likely due to that multiperiod planning takes long-term food deterioration rates and future incoming donations into account whereas single-period planning does not. Although the multiperiod planning provides better solutions, the approach requires accurate predictions of future incoming donations, deterioration rates, and expiry dates. Therefore, food banks should gauge the quality of their forecasts and select the planning horizon length accordingly.

6 | CONCLUSION

To conclude, we return to the four research questions posited in Section 1. (1) *Are substantial deviations from perfect equity necessary for improving effectiveness?* No, our case study demonstrates that significant gains in effectiveness (i.e., the quantity and quality of food distributed) are possible when small equity deviations are strategically implemented. (2) *How should food banks set target equity deviations that best balance the equity/effectiveness trade-off?* Food banks should strive for small deviations (1% or 2%) with each distribution. This approach results in zero waste for the scenarios considered in our case study. Moreover, the quantity and quality of food distributed can also be improved up to 24% with only a modest increase in the length of the equity window (two periods). Lastly, food banks should proactively incorporate equity deviations in their initial distribution each period as opposed to the reactive approach currently used in practice that may lead to food waste. (3) *What effects do food deterioration rates have on determining appropriate target deviations from perfect equity?* It depends on county capacities. Under low-capacity scenarios, there is little or no benefit to setting large equity deviation targets to mitigate the negative effects of rapid food deterioration. Increasing the degree of inequity allowed only makes sense for this purpose if equity is a more limiting factor than capacity. (4) *What effect does the proposed quality-based equity metric have on traditional quantity-based equity?* Not surprisingly, there is a trade-off between them. However, it is worth mentioning that the two equity metrics do not affect effectiveness in the same way. Traditional weight-based equity requires larger deviations from perfect equity relative to deviations from the value-based equity metric in order to achieve the same level of effectiveness.

There are many possibilities for future research that can help further improve food bank operations. For instance, routing aspects of this problem may be studied by considering the cost of transporting food to beneficiaries. Perhaps more importantly, capacity limitations of the food bank can also be represented in future work. Food banks rely upon volunteer labor, and the shortage of volunteers due to the COVID-19 pandemic suggests that limited capacity at food banks is an important issue. Finally, agencies may prefer to receive certain types of items based on their locations, capacities, and the populations they serve. Hence, accounting for the agency preferences in allocation decisions presents another potential future research opportunity.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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