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Integrated foodbank network design: Model and a case study

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ABSTRACT

To address the UN's zero hunger goal (SDG 2), scattered and isolated initiatives by nonprofit organizations towards operating foodbanks are generally ineffective in developing countries where the foodbank ecosystem is at a preliminary stage. Establishing an integrated system comprising entities such as donors, foodbanks, food recovery and redistribution agencies (FRRA), and beneficiaries can be quite complex due to an underlying hierarchy, scale of operation, types of donors, and the severity of food insecurity of the beneficiaries. In this work, we present a strategic mixed-integer programming model to design an integrated foodbank network towards achieving an efficient, effective, and equitable food distribution mechanism for food-insecure beneficiaries while accounting for their age profile and nutritional requirements. We ensure cost-efficiency by minimizing the total system cost, effectiveness by discouraging food waste and unmet demand via charging penalties, and equity by adopting five variants of an egalitarian approach. We conduct a case study with a mix of real and realistically estimated data to design a foodbank network in Delhi (India) and present detailed analyses with insights for the practitioners. Specifically, the effects of foodbanks' initial capacities, budget and strategic-to-operational cost constraints on the solution are identified. Among important observations, our analyses highlight when initiatives for collecting more ready-to-eat foods might be taken to relieve the pressure on the integrated system, and also help in identifying the conditions when investment in capacity building serves the beneficiaries' interests better than direct spending.

1. Introduction

To date, 'zero hunger' remains an extremely challenging goal to achieve by 2030 (United Nations, 2023b) for both the developing and developed countries that are exposed to extreme hunger and malnutrition in a conflict-struck post-pandemic world. In 2021, 12.5% of U.S. households with children and 10.2% of households in general remained food-insecure (U.S. Department of Agriculture, 2023). In 2022, as per United Nations (2023b), while about 735 million people (9.2% of the global population) were exposed to chronic hunger, an estimated 2.4 billion people experienced moderate to severe food insecurity, which indicates an acute lack of access to required nourishment. In the 2022 Global Hunger Index (GHI), India, one of the emerging and developing countries with 17.7% of global population in 2023, was ranked 107th out of the 121 countries with the score of 29.1 (level: *serious*) (Global Hunger Index, 2023). While the global food insecurity level is alarmingly high, the Food Loss Index (FLI) [connected to UN SDG 12.3.1A] shows a staggering global food loss of 13.8% in 2019 (i.e., around US $400 billion), making the *food loss and waste* reduction (UN SDG target 12.3) (United Nations, 2023a) an associated challenge (Akkaş and Gaur, 2022).

To address this humanitarian crisis of hunger, the United Nations (2023b) urges for 'coordinated action and policy solutions' that can be instrumental in making 'a fundamental shift in trajectory', and help 'to achieve the 2030 nutrition targets'. Foodbanks as nonprofit organizations can play an important role in fighting hunger by becoming aggregators of surplus food having varying shelf lives (ranging from fresh produce to cooked food) from different sources such as grocers, growers, and supermarkets, and distribute the same to the needy population (Nair et al., 2017). Despite facing challenges, the foodbank ecosystem has become mature over the decades in developed countries. For example, Feeding America, the largest foodbank network in the US started in the late 1960s (Feeding America, 2023). The Trussell Trust, with a network of over 1200 foodbanks in the UK, provide emergency food and support to the poor since 1997 (The Trussell Trust, 2023). In 1981, Edmonton's Food Bank started its journey as the first foodbank in Canada (Edmonton's Food Bank, 2023). However, despite facing food insecurity at a *serious* level in the GHI score, India witnessed

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its first foodbank only in 2012 (The Hindu, 2012). Developments in the following years have also been driven primarily by philanthropic initiatives of individuals and small groups to address the local needs, lacking any broader plan or systems thinking (Dubey and Tanksale, 2022). In India, the majority of foodbanks and the related nonprofit organizations that are involved in food rescue and redistribution, operate in silos. While in many western countries (some are mentioned above), large foodbanks with refrigerated warehouses have adequate capacities to collect, store, sort, pack and deliver the food packets to the needy people, most small size Indian foodbanks primarily collect cooked food from small donors and distribute those locally to the needy people within a very short timeframe due to perishability of the recovered food. Instead, a coordinated foodbank system with capacity-sharing abilities can achieve a greater synergy with active involvement of government, corporates, and industry partners as the stakeholders. To develop and operationalize such an integrated system, effective decision support tools are essential for the collection, storage, forecasting of supply/demand, and effective distribution through the established logistics network.

In a recent initiative, the Food Safety and Standards Authority of India [FSSAI] (2023) has created the 'Indian Food Sharing Alliance' (IFSA), a platform to encourage 'food donation, stop food waste and food loss in the country'. Our research is motivated by the aim of IFSA to create a 'network by including food collection agencies, citizens, food businesses, corporates, civil society organizations, volunteers, government and local bodies in a coordinated manner' (Food Safety and Standards Authority of India [FSSAI], 2023). In this paper, with a mathematical modeling approach, we propose an integration of different isolated efforts that can help in creating a foodbank ecosystem in developing countries where the concept is relatively new. Specifically, using a mixed-integer programming (MIP) model (see Section 3) we present a case - with a mix of real and realistically estimated parameters - of designing a strategic network in Delhi (India) by integrating two distinct tiers of donors, beneficiaries, foodbanks, and food recovery and redistribution agencies (FRRA) (see Section 4). While Tier-I includes large institutional donors and foodbanks with large capacities to provide nutritional supplements to beneficiaries at certain schools, old-age homes, etc., Tier-II involves small-scale donors, FRRAs with limited capacities to serve beneficiaries at slums/shelters exposed to extreme food insecurity. Our proposed model can be used by the social planners as a centralized decision making tool, which, in turn, can aid the authorities such as FSSAI in their policymaking towards addressing the food insecurity and food waste issues effectively. Furthermore, the model can aid in exploring the effects of imposing various practical conditions and restrictions on the solution, thereby assist in gaining insights towards developing more impactful policies. Specifically, our model can be instrumental in answering the following research questions.

1. Given the donation quantities from donors of different capabilities, beneficiaries' demand, set of existing and potential foodbanks and FRRAs with certain options of capacity increase, which foodbanks and FRRAs to select for constructing an integrated network by connecting them with appropriate donors and beneficiaries?
2. How the age profile and nutritional requirements of beneficiaries of different socio-economic backgrounds can be included in strategic decision making?
3. How would the proposed integrated system respond to supply and demand uncertainties, and a budget constraint?
4. What is the value of integrating two tiers that *presently operate in silos*?

Our base model designs the strategic network while addressing 3E's, i.e., efficiency, effectiveness, and equity. Cost-*efficiency* and *effectiveness* are addressed together by minimizing the system cost and charging penalties for demand shortage (i.e., inability to address food insecurity), uncollected donations as well as collected but unused donations (i.e., inability to address food waste) (see Section 3.2). Specifically, the objective function minimizes the sum of fixed costs of adding foodbanks and FRRAs, their capacity expansions (if needed), costs of food procurement and distribution among different network entities, and three penalties for: (i) unmet demand, (ii) uncollected food at donors, as well as (iii) collected but unused food at the foodbanks/FRRAs. We present a detailed analysis of different egalitarian approaches of *equity* consideration in Section 5.9. Our extensive numerical analyses (see Sections 5.1–5.8) with various key observations should provide insights and help the policymakers in appreciating the advantage of designing an integrated system to address food insecurity (see Section 5.6).

This paper contributes to the literature in several ways. First, we present a new MIP model to design an integrated network comprising donors, foodbanks, FRRAs, and beneficiaries with different levels of nutritional needs. Our approach comprehensively includes both *periodic* (weekly or monthly) bulk donations of large shelf-life foods by institutional donors and *daily* donations of short self-life (cooked) food (more details on operational frequencies in Section 3.1) by small-scale donors, thus, helps in addressing together the food insecurity and food waste issues. Second, our study explicitly considers the conversion of different types of donated foods with different nutritional values into predetermined configurations of food packets to fulfill the varied nutritional needs of beneficiaries of different age groups with exposure to different socio-economic vulnerabilities. Third, numerical analyses of our case study with the real and realistically estimated parameters, set at the Delhi National Capital Region (NCR) in India, elicit interesting insights that can aid a decision-maker in the centralized, integrated, foodbank ecosystem.

The remainder of this paper is organized as follows. Section 2 presents a review of related literature, followed by a discussion of our problem setting and the mathematical model in Section 3. Next, we present a case study in Section 4 along with the base model's solution. In Section 5, we discuss different numerical analyses to illustrate the effects of changing various model parameters on the solution. Finally, we conclude in Section 6 with a discussion on the usability of certain insights from this research to a decision-maker and an indication of a few future research directions.

2. Related literature

Although the foodbank system has been well-established in Northern America since the 1960's, it gradually gained attention in the European and Asian countries over the past years. Due to foodbank's important role in addressing food insecurity, research interests have evolved in different areas of foodbank operations and food aid distribution, for example, behavioral aspects of foodbank users (Tarasuk and Eakin, 2005), nutritional analysis of the donation (Peters et al., 2021), prediction of donation (Davis et al., 2016), donor-beneficiary matching (Dalal, 2022), optimizing the food distribution effort by route planning (Govindan et al., 2014; Nair et al., 2017; Reihaneh and Ghoniem, 2018), application of mobile pantries for distribution (Stauffer et al., 2022), food aid modality selection (Rancourt et al., 2015; Sahinyazan et al., 2021).

Since we propose designing a strategic integrated foodbank network to enable donation collection, packaging, and distribution by explicitly considering the varying needs of beneficiaries and the nutritional values of donated and procured food, we primarily review the literature on foodbank network design with the emphasis on *cost-efficiency, effectiveness, and equity*, while also keeping a focus on the nutritional aspects of the distributed food. For reviewing diverse aspects of foodbank-related research – which is out of our scope – we refer the reader to Dubey and Tanksale (2022) and Mahmoudi et al. (2022).

Network design: On the foodbank network (re-)design problem, Martins et al. (2019) consider a system comprising donors, foodbanks, and charitable agencies to serve the beneficiaries. Their model's decisions include opening foodbanks at potential locations, closing existing foodbanks, storage and transportation capacity acquisition, food purchase, and transportation. The authors adopt a triple bottom line approach with economic, environmental, and social objectives, and analyze their tradeoffs using a lexicographic approach in a case study of foodbank network from Portugal. Kaviyani-Charati et al. (2022) propose a multi-period, two-stage stochastic programming model to design a similar network with donors, foodbanks, and demand zones experiencing demand uncertainty, and apply the same on a case study on foodbanks in Tehran, Iran. They minimize food waste and ensure the safety of surplus food through a cold chain while optimizing social performance in addition to overall cost reduction. In a related study on Iran, Ghahremani-Nahr et al. (2023) consider foodbank location, allocation, routing, and inventory decisions with the primary emphasis on the nutritional value of a predefined food basket at foodbanks. They propose a multi-objective robust optimization model and majorly contribute with novel solution approach. In a recent study, Reusken et al. (2023) make capacity acquisition and network planning decisions for foodbanks, while focusing on strategic utilization of available budgets to maximize the number of beneficiaries that can be supported by the network. To the best of our knowledge, the above-mentioned four literature focusing on foodbank network designing and planning are most relevant to our work.

Efficiency, effectiveness, and equity: Considering the importance of 3E's, i.e., efficiency, effectiveness, and equity (also aligned to UNSDG 10: reduced inequalities) in nonprofit operations, several recent works emphasize these aspects. Martins et al. (2019) ensure equity in the distribution of donated food among all charities by embedding it into social objectives while incorporating efficiency and effectiveness in the economic and environmental objective functions. These 3E's also play a crucial role in food distribution (Sengul Orgut et al., 2016; Hasnain et al., 2021) and routing problems for food rescue pickup/delivery operations (Nair et al., 2017; Rey et al., 2018). In foodbank literature, increasing the number of beneficiaries served or the total quantity of food (re)distributed is a common measure of effectiveness. Alkaabneh et al. (2021) undertake effectiveness as a measure of the nutritional value of the allocated food to the agency. However, considering the prevalence of the food waste problem, we address effectiveness by reducing waste by collecting surplus food at the donors, penalizing any unused donation, and minimizing the unmet demand of beneficiaries by charging different penalties. In literature, the 3E's are commonly addressed by defining multiple objectives and analyzing their tradeoffs using multi-objective optimization. In our work, efficiency and effectiveness are captured in a single composite objective function. We conduct a separate analysis on five equity variants by adopting the egalitarian approach of minimizing the maximum value of some linear function of unmet demand experienced by beneficiaries (see details in Section 5.9).

Nutritional requirements: Food, being the central theme of the foodbank system's fight against hunger, must contain the nutrients that are essential to meet the recommended daily intake requirement of the beneficiaries. However, many studies limit their scope to charitable agencies and overlook the details of the end beneficiaries' requirements by taking an aggregated demand. Consequently, those studies cannot distinguish adults and children exposed to hunger at different severities. In the context of foodbank network design, to the best of our knowledge, only (Ghahremani-Nahr et al., 2023) consider maximizing the nutritional values of the food packets. Although some health and nutrition literature highlight the distinct needs of different age groups concerning nutrients, this issue is inadequately addressed in the existing foodbank network design and planning literature. Campbell et al. (2013) conduct a comprehensive survey on 137 US foodbanks to document, understand, and analyze the culture, capacities, and practices related to the nutrition of foodbanks. Bazerghi et al. (2016) investigate whether the beneficiaries' nutritional requirements are met by foodbanks. Both studies discover inadequacies in the foodbanks' programs and recommend more attention towards aligning with the nutrition policies. This health and nutrition literature helps us in devising the concept of preparing packets at foodbanks for distribution from the available food following the predefined configurations to meet the diverse nutritional needs of beneficiaries. Moreover, we assign priority weights to different beneficiary groups to facilitate demand fulfillment in a resource-limited situation.

Geographical context: The literature contains several case studies on foodbank system development in countries such as Portugal, Iran, Kenya, Netherlands, etc., however, no study has yet been done on the network design of foodbanks in India, the most populous country experiencing food insecurity at a serious level. Several unique characteristics distinguish the challenges before the Indian foodbank system from its counterparts in other nations. Typically, many small foodbanks lacking adequate logistical capacities operate in silos at local levels at different parts of India. The benefits of sharing capacities are not realized by those entities. Also, from the point of view of nutritional need fulfillment, the types and quantities of cooked food items collected and distributed by those small foodbanks often prove to be inadequate. Therefore, as highlighted by Dubey and Tanksale (2022), the Indian foodbanking system urgently needs institutionalization to bring efficiency and synergy in their operations. To this end, development of required infrastructure in terms of storage warehouses, cold storages, collection and distribution mechanisms with active engagement of government, corporate/industry, and the society is essential. Our proposed optimization model for designing an integrated system along with managerial insights generated from analyses, can help the policymakers. To the best of our knowledge, no foodbank network design problem has yet been studied in the Indian context - a gap that our research intends to fill by applying our proposed optimization model on a realistic case study on foodbank system of Delhi, the capital city of India.

3. Problem setting and model formulation

In this section, we briefly present our proposed integrated foodbank system, followed by a MIP model for designing the network. We also present an illustrative toy instance solution.

3.1. Problem description

Unlike several developed countries where a foodbank ecosystem is already established comprising entities such as donors, foodbanks, partner agencies, and beneficiaries, in many developing countries (e.g., India) this is an emerging domain with opportunities to strengthen the system by systematically integrating the isolated and localized small social entrepreneurial initiatives. Based on the scale, the scope of operation, capacity, and stakeholder characteristics, we broadly classify the foodbank system into two tiers. Large foodbanks, equipped with large storage facilities, vehicles, paid staff, and volunteers, can collect bulk donations (e.g., food grains, pulses, packaged foods with long shelf life) from institutional donors such as retailers, growers, and grocers. The donation stored at the foodbank's warehouse is later converted to packets that are distributed to institutional beneficiaries such as adult care homes, orphanages, and schools attended by economically backward communities, to *supplement* their nutritional needs. We would call such a system comprising "large donor → foodbank → institutional beneficiary" as *Tier-I*. Many smaller food recovery and redistribution initiatives operate locally at towns and small cities to serve the marginalized section of society such as malnourished slum-dwellers, homeless people staying at shelters, etc. Such beneficiaries are in dire need of extensive food support, unlike *supplements* for the Tier-I beneficiaries. These small *agencies* (often function informally) with a handful of volunteers get engaged in primarily collecting various ready-to-eat and cooked food donations from sources with excess food

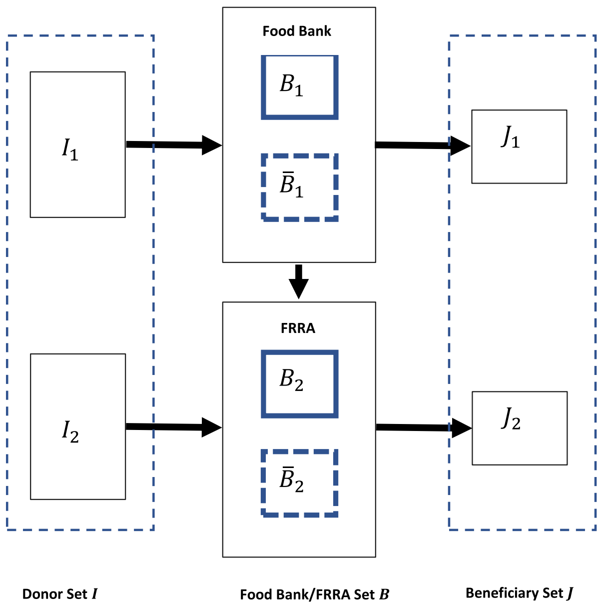


Fig. 1. (Color online) Schematic diagram of sets (notations in Tables 1–3).

on regular basis (e.g., student hostels, office canteens, army barracks, restaurants, etc.), and attempt to distribute their collection on the same day due to lack of storage/refrigeration facilities and limited vehicular capacities (generally use small cars or motorbikes). We refer to these entities as the Food Recovery and Redistribution Agencies (FRRA) by following the terminology used in the (IFSA, 2023) website. Some of these FRRAs may also receive donations from a Tier-I foodbank operating in their proximity. However, low capacities and extremely limited shelf life of the donated food restrict them to work locally, where distribution can be completed within a few hours. We would call this system comprising "small donor → FRRA → individual beneficiary" as the *Tier-II*. These two tiers, representing two very different systems, often operate in silos in practice, lacking any overarching framework.

Our research proposes a strategic integration of the aforementioned two tiers to make a holistic foodbank ecosystem. Fig. 2 presents a schematic diagram of the *proposed system* with the model parameters and decision variables. For notations, we refer the reader to Tables 1–3. Given the sets of donors, beneficiaries, existing as well as potential (new) foodbanks and FRRAs (refer to Fig. 1), our model makes strategic decisions on selecting potential foodbanks/FRRAs for inclusion in an integrated network, capacity expansion decisions for existing or potential foodbanks, and operational decisions of connecting donors and beneficiaries to the operating foodbanks/FRRAs of the same tier, food procurement (if needed), and flows among these network entities. In order to realistically represent the decision variables, we use a mix of binary, nonnegative integer, and nonnegative continuous variables (refer to Table 2). For instance, while for the strategic decisions related to foodbank/FRRA opening and installation of discrete storage capacity levels we use binaries; to determine the number of vehicles, personnel hired, food packets prepared and dispatched, we require nonnegative integer variables as they are discrete quantities. However, to represent various utilized capacities and flow of food within the network, we employ nonnegative continuous variables, as the lows of food (donated or procured) occur in bulk quantities in reality. Therefore, our mathematical model for the strategically integrated foodbank network design becomes a mixed-integer programming (MIP) model to appropriately represent various decisions. Since nonprofit systems generally experience tight budgets, our model finds the solution cost-effectively by minimizing the sum of strategic network building cost, various tactical and operational costs associated with flows, and penalties to discourage both food shortage and waste. This way, our model addresses both economic *efficiency* (cost minimization) and operational *effectiveness* (reducing shortage and waste). Furthermore, in Section 5.9, we extensively discuss *equity*, thus, our approach addresses the important 3E's in nonprofit operations management.

The beneficiary nodes have different beneficiary types $\pi \in \Pi$, e.g., child and adult. While $D_{\pi j}$ represents the demand of type π beneficiary at the node j, unmet demand at that node in terms of the number of type π beneficiaries, is represented by $\lambda_{\pi j}$. If needed for fulfilling the beneficiaries' demand, the model can open potential foodbanks/FRRAs $b \in \bar{B}_1 \cup \bar{B}_2$, i.e., at the respective tier, incurring fixed cost C_b (associated decision variable x_b). A donor i_1 having total available donation quantity Q_{fi_1}, sends $q_{fi_1 b_1}$ to an operative foodbank b_1. If θ_{fi_1} quantity remains uncollected at i_1, as mentioned before, to discourage it, a penalty is charged. If donation received at a Tier-I foodbank b_1 is inadequate, the model can suggest procuring μ_{fb_1} quantity of permitted food type f (indicator $\alpha_f = 1$) at the unit cost Γ_f. Note that a Tier-II FRRA b_2 does not purchase food, but, can receive $q_{fb_1b_2}$ quantity of food type f transferred from a Tier-I foodbank b_1. Note here, since Tier-I mostly handles uncooked food donations and purchases, we consider a Tier-I foodbank b can have an initial storage capacity S_b^0, with possible increments S_l at levels $l \in L$ at the cost of C_{lb} (associated decision variable y_{lb}). However, Tier-II FRRAs being small and primarily handling cooked/ready-to-eat food with low shelf life, do not have storage capacity. Foodbanks and FRRAs have initial transport capacities T_b^0 with possible increase T_k at the cost of C_k (associated decision variable t_{kb}). Similarly, the workforce capacity of a foodbank/FRRA b can be increased from its initial level (volunteers V_b^0 and paid staff ρ_b^0), considering the staff hiring cost C^M (associated decision variable p_b).

Fig. 3 further elaborates on the food flow through the proposed system. Upon donation receipt, purchase (if needed), and transfer, the net quantity $\hat{q}_{fb}$ is allocated as $\omega_{f\pi b}$ among different beneficiary types ($\pi \in \Pi$). Next, discounting any unused food quantity $\gamma_{f\pi b}$ at the foodbank/FRRA b (discouraged by penalty), the net available food allocated for beneficiary π is converted to $\tau_{\pi bp}$ packets (shown in the rectangles within Fig. 3), prepared as per predefined packet composition (represented by $\beta_{f\pi mp}$) to meet the beneficiaries' nutritional needs (further elaborated in Section 4). From $\tau_{\pi bp}$ packets, our MIP model further determines the appropriate allocation of $\vartheta_{\pi bjp}$ packets of type p for beneficiary type π living at node j (shown along the arrows from foodbanks to beneficiaries).

Finally, we mention the differences in operational frequencies between the two tiers (also in Table 3). While Tier-I foodbanks handle bulk inflows on a *weekly* basis, Tier-II FRRAs receive smaller donations *daily* (parameter T_m^{IN}). Moreover, all the foodbank → FRRA transfers also occur on *daily* basis (parameter T_1^{TR}). Therefore, donation inflow-handling frequencies (parameter T_m^H) are also on a weekly and daily basis for the Tier-I foodbanks and Tier-II FRRAs, respectively. However, as outflows from foodbanks/FRRAs of both tiers occur *daily* (parameter T_m^{OUT}), the packaging frequency T_m^P is also on a daily basis. Thus, the centralized decision maker of the proposed foodbank network can run our mathematical model on every weekend to plan ahead for the upcoming week. Next, we present our mathematical model with all notations.

3.2. Notations and mathematical model

We present the notations for sets and indices, decision variables, and parameters for the proposed mathematical model in Tables 1, 2, and 3, respectively.

Formulation

$$[\text{P}]\ \text{Min } Z = \sum_{b\in\bar{B}_1\cup\bar{B}_2} C_b x_b + \sum_{l\in L}\sum_{b\in B_1\cup\bar{B}_1} C_{lb} y_{lb} + \sum_{k\in K} C_k\left(\sum_{b\in B} t_{kb}\right)$$
$$+ \sum_{b\in\bar{B}_1\cup\bar{B}_2} C^M(p_b + \rho_b^0 x_b) + \sum_{b\in B_1\cup B_2} C^M(p_b + \rho_b^0) + \sum_{f\in F}\sum_{b\in B_1\cup\bar{B}_1} \alpha_f \Gamma_f \mu_{fb}$$

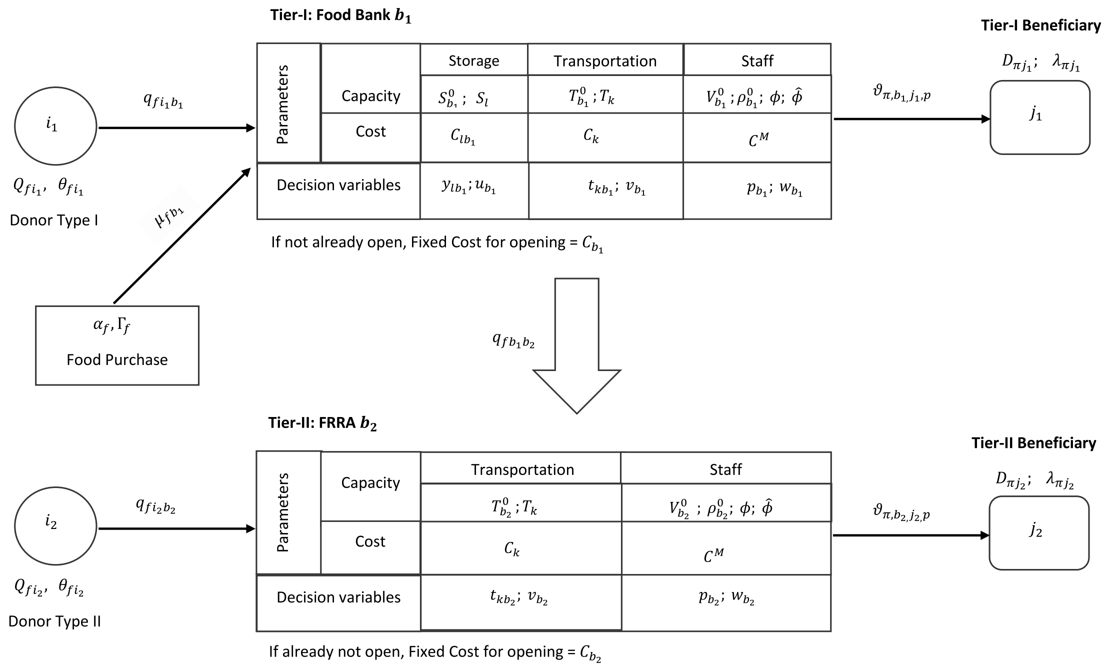


Fig. 2. Schematic diagram of *proposed system*: parameter and decision variables in Tables 1–3.

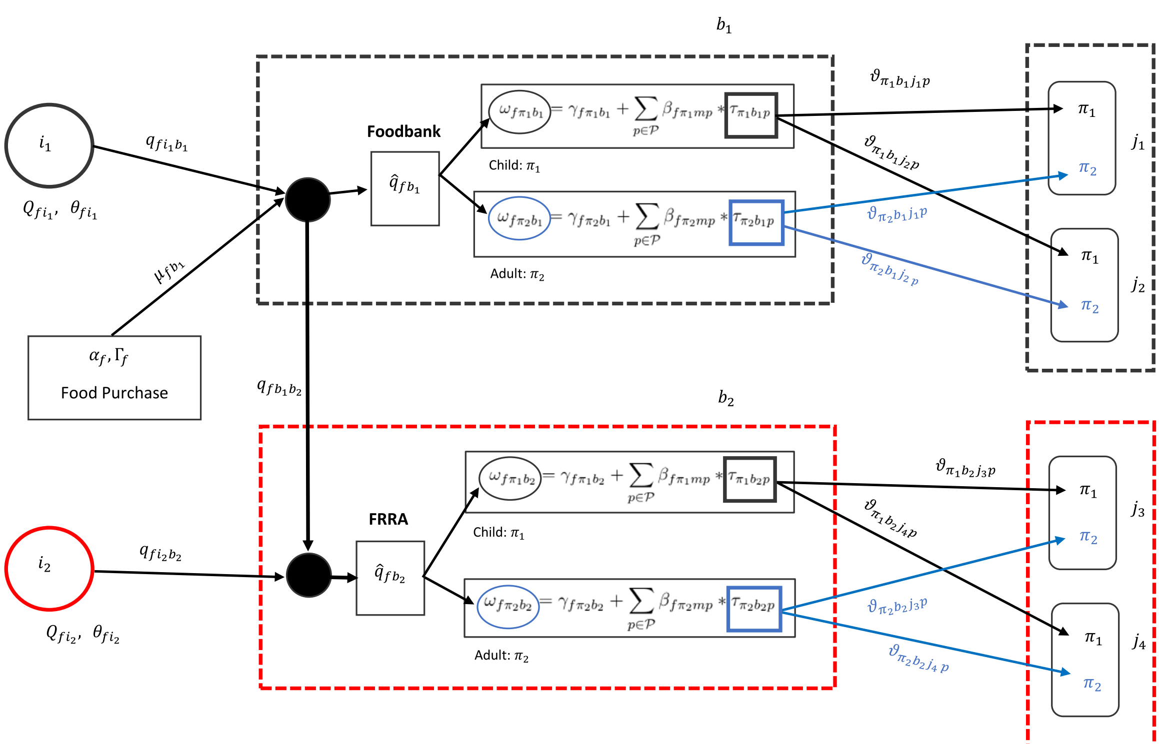


Fig. 3. (Color online) Schematic diagram of flows through *proposed system* (notations in Tables 1–3).

$$+\sum_{f\in F}\sum_{\substack{(i,b):i\in I_m;\\ b\in B_{m'}\cup\bar{B}_{m'}\\ m,m'\in\mathcal{M},m\neq m'}} C_{ib}q_{fib} + \sum_{f\in F}\sum_{b\in B_1\cup\bar{B}_1}\sum_{b'\in B_2\cup\bar{B}_2} C_{bb'}q_{fbb'}$$

$$+\sum_{\substack{(b,j):b\in B_{m'}\cup\bar{B}_{m'};\\ j\in J_m;m,m'\in\mathcal{M},m\neq m'}} C_{bj}\left(\sum_{\pi\in\Pi}\sum_{p\in\mathcal{P}}\vartheta_{\pi bjp}\right)$$

$$+\sum_{m\in\mathcal{M}} P_m^{(1)}\left(\sum_{f\in F}\sum_{i\in I_m}\theta_{fi}\right)+\sum_{m\in\mathcal{M}}P_m^{(2)}\left(\sum_{f\in F}\sum_{\pi\in\Pi}\sum_{b\in B_m\cup\bar{B}_m}\gamma_{f\pi b}\right)$$

$$+\sum_{\pi\in\Pi}\sum_{m\in\mathcal{M}}P^{(3)}_{\pi m}\left(\sum_{j\in J_m}\lambda_{\pi j}\right) \tag{1}$$

subject to

Table 1
List of sets and indices for the mathematical model.

Entity	Notation	Description	Index
Network	$\mathcal{M}$	Set of tiers	m
Donor	I_1	Set of donors who deliver food to Tier-I foodbanks	i
	I_2	Set of donors who deliver food to Tier-II FRRAs	
	I	Set of all donors	
Foodbank	B_1	Set of existing Tier-I foodbanks	b
	B_2	Set of existing Tier-II FRRAs	
	$\bar{B}_1$	Set of candidate Tier-I foodbanks	
	$\bar{B}_2$	Set of candidate Tier-II FRRAs	
	B	Set of all foodbanks and FRRAs $\left(B_1 \cup B_2 \cup \bar{B}_1 \cup \bar{B}_2\right)$	
Capacity	L	Storage capacity levels (Only at Tier-I foodbanks)	l
	K	Transport capacity alternatives (type of vehicles)	k
Beneficiary	Π	Set of beneficiary type	π
	J_1	Set of Tier-I beneficiary nodes	j
	J_2	Set of Tier-II beneficiary nodes	
	J	Set of all beneficiary nodes	
Food items	F	Set of food items	f
	$\mathcal{P}$	Set of food packet types	p

Table 2
List of decision variables for the mathematical model.

x_b	= 1 if foodbank/FRRA $b \in \bar{B}_1 \cup \bar{B}_2$ is open, 0 otherwise
y_{lb}	= 1 if storage capacity level $l \in L$ is installed at Tier-I foodbank $b \in B_1 \cup \bar{B}_1$, 0 otherwise
t_{kb}	Number of vehicles of type $k \in K$ hired at foodbank/FRRA $b \in B$
p_b	Number of personnel hired at foodbank/FRRA $b \in B$
u_b	Effective storage capacity at Tier-I foodbank $b \in B_1 \cup \bar{B}_1$
v_b	Effective transportation capacity at foodbank/FRRA $b \in B$
w_b	Effective staff capacity at foodbank/FRRA $b \in B$
q_{fib}	Quantity of food $f \in F$ flow from donor i to foodbank/FRRA b (across-tier flow not allowed, i.e., $q_{fib} := 0$ if $i \in I_1, b \in B_2 \cup \bar{B}_2$ and $q_{fib} := 0$ if $i \in I_2, b \in B_1 \cup \bar{B}_1$)
μ_{fb}	Quantity of food $f \in F$ procured at Tier-I foodbank $b \in B_1 \cup \bar{B}_1$
$q_{fbb'}$	Quantity of food $f \in F$ transferred from Tier-I foodbank $b \in B_1 \cup \bar{B}_1$ to Tier-II FRRA $b' \in B_2 \cup \bar{B}_2$ (i.e., $q_{fbb'} := 0$ if $b \in B_2 \cup \bar{B}_2, b' \in B$)
$\hat{q}_{fb}$	Quantity of food $f \in F$ available for distribution at foodbank/FRRA $b \in B$
θ_{fi}	Uncollected food type $f \in F$ at donor location $i \in I$
$\omega_{f\pi b}$	Quantity of food $f \in F$ for beneficiary type $\pi \in \Pi$ at foodbank/FRRA $b \in B$
$\tau_{\pi bp}$	Food packets of type $p \in \mathcal{P}$ for beneficiary type $\pi \in \Pi$ made at foodbank/FRRA $b \in B$
$\vartheta_{\pi bjp}$	Packet type $p \in \mathcal{P}$ sent from foodbank/FRRA $b \in B$ for beneficiary type $\pi \in \Pi$ staying at node $j \in J$
$\gamma_{f\pi b}$	Food $f \in F$ for beneficiary type $\pi \in \Pi$ remained unused at foodbank/FRRA $b \in B$ (i.e., collected from donor but not distributed)
$\lambda_{\pi j}$	Unmet demand of beneficiary type $\pi \in \Pi$ at beneficiary location $j \in J$

$$\sum_{l\in L} y_{lb} \le 1 \qquad \forall b \in B_1 \tag{2}$$

$$\sum_{l\in L} y_{lb} \le x_b \qquad \forall b \in \bar{B}_1 \tag{3}$$

$$u_b = S_b^0 + \sum_{l\in L} S_l y_{lb} \qquad \forall b \in B_1 \tag{4}$$

$$u_b = S_b^0 x_b + \sum_{l\in L} S_l y_{lb} \qquad \forall b \in \bar{B}_1 \tag{5}$$

$$v_b = T_b^0 + \sum_{k\in K} T_k t_{kb} \qquad b \in B_1 \cup B_2 \tag{6}$$

$$v_b = T_b^0 x_b + \sum_{k\in K} T_k t_{kb} \qquad b \in \bar{B}_1 \cup \bar{B}_2 \tag{7}$$

$$t_{kb} \le U^t \qquad \forall k \in K, b \in B_1 \cup B_2 \tag{8}$$

$$t_{kb} \le U^t x_b \qquad \forall k \in K, b \in \bar{B}_1 \cup \bar{B}_2 \tag{9}$$

$$w_b = (V_b^0 + \rho_b^0) + p_b \qquad \forall b \in B_1 \cup B_2 \tag{10}$$

$$w_b = (V_b^0 + \rho_b^0) x_b + p_b \qquad \forall b \in \bar{B}_1 \cup \bar{B}_2 \tag{11}$$

$$p_b \le U^p \qquad \forall b \in B_1 \cup B_2 \tag{12}$$

$$p_b \le U^p x_b \qquad \forall b \in \bar{B}_1 \cup \bar{B}_2 \tag{13}$$

$$\sum_{b\in B_m \cup \bar{B}_m} q_{fib} + \theta_{fi} = Q_{fi} \qquad \forall f \in F, i \in I_m, m \in \mathcal{M} \tag{14}$$

$$\sum_{f\in F}\sum_{i\in I_m} q_{fib} \le T_m^{IN} v_b \qquad \forall b \in B_m \cup \bar{B}_m, m \in \mathcal{M} \tag{15}$$

$$\sum_{f\in F}\sum_{b'\in B_2 \cup \bar{B}_2} q_{fbb'} \le T_1^{TR} v_b \qquad \forall b \in B_1 \cup \bar{B}_1 \tag{16}$$

$$\sum_{f\in F} \hat{q}_{fb} \le T_m^{OUT} v_b \qquad \forall b \in B_m \cup \bar{B}_m, m \in \mathcal{M} \tag{17}$$

$$\sum_{f\in F}\sum_{i\in I_1} q_{fib} + \sum_{f\in F} \alpha_f \mu_{fb} \le T_1^H (\varphi w_b) \qquad \forall b \in B_1 \cup \bar{B}_1 \tag{18}$$

Table 3
List of parameters for the mathematical model.

Capacity	
S_b^0	Initial storage capacity at Tier-I foodbank $b \in B_1 \cup \bar{B}_1$
S_l	Storage capacity addition at level $l \in L$ (only for a Tier-I foodbank)
T_b^0	Initial transport capacity at foodbank/FRRA $b \in B$
T_k	Transport capacity addition by including a vehicle of type $k \in K$
V_b^0	Number of volunteers at foodbank/FRRA $b \in B$
ρ_b^0	Number of paid staff at foodbank/FRRA $b \in B$
U^t, U^p	upper bounds on transport and staff capacity addition, respectively
φ	Donation quantity handled by one person per day
$\hat{\varphi}$	Number of food packets handled by one person per week
Demand and donation	
$D_{\pi j}$	Demand at beneficiary location $j \in J$ for beneficiary type $\pi \in \Pi$
Q_{fi}	Quantity of food $f \in F$ available for donation at donor $i \in I$
Nutrition	
$\beta_{f\pi mp}$	Quantity of food $f \in F$ in a packet of type $p \in \mathcal{P}$ for beneficiary type $\pi \in \Pi$ belonging to tier $m \in \mathcal{M}$
α_f	= 1, if food $f \in F$ is allowed to be procured by foodbank, else 0
Costs	
C_b	Cost of opening a new foodbank/FRRA
C_{lb}	Cost of installing storage capacity of level $l \in L$ at Tier-I foodbank $b \in B_1 \cup \bar{B}_1$
C_k	Cost of adding a vehicle of type $k \in K$
C^M	Cost of hiring a staff at foodbank/FRRA
Γ_f	Unit procurement cost for food item $f \in F$
α	Unit transportation cost
d_{ij}	Distance between node pair (i, j)
C_{ij}	$= \alpha d_{ij}$, transportation cost between appropriate node pairs (i, j) in network
$P_m^{(1)}$	Penalty for uncollected donation from donor of Tier $m \in \mathcal{M}$
$P_m^{(2)}$	Penalty for collected but unused donation at a foodbank/FRRA of Tier $m \in \mathcal{M}$
$P_{\pi m}^{(3)}$	Penalty for unmet demand of beneficiary type $\pi \in \Pi$ belonging to Tier $m \in \mathcal{M}$
Frequency of operations	
T_m^{IN}	Inflow frequency at foodbank/FRRA of Tier $m \in \mathcal{M}$; $T_1^{IN} = 1$ (weekly), $T_2^{IN} = 7$ (daily)
T_1^{TR}	Transfer frequency from foodbank of Tier $m = 1$; $T_1^{TR} = 7$ (daily)
T_m^{OUT}	Foodbank/FRRA → beneficiary distribution frequency; $T_m^{OUT} = 7$ (daily), $m \in \mathcal{M}$
T_m^H	Inflow handling frequency at foodbank/FRRA; $T_1^H = 1$ (weekly), $T_2^H = 7$ (daily)
T_m^P	Packet sending frequency from foodbank/FRRA of Tier m; $T_m^P = 7$ (daily), $m \in \mathcal{M}$

$$\sum_{f\in F}\sum_{i\in I_2} q_{fib} + \sum_{f\in F}\sum_{b\in B_1\cup\bar{B}_1} q_{fb'b} \le T_2^H(\varphi w_b) \quad \forall b \in B_2 \cup \bar{B}_2 \tag{19}$$

$$\sum_{\pi\in\Pi}\sum_{p\in\mathcal{P}} \tau_{\pi bp} \le T_m^P \hat{\varphi} w_b \quad \forall b \in B_m \cup \bar{B}_m, m \in \mathcal{M} \tag{20}$$

$$\hat{q}_{fb} = \sum_{i\in I_1} q_{fib} + \alpha_f \mu_{fb} - \sum_{b'\in B_2\cup\bar{B}_2} q_{fbb'} \quad \forall f \in F, b \in B_1 \cup \bar{B}_1 \tag{21}$$

$$\hat{q}_{fb} = \sum_{i\in I_2} q_{fib} + \sum_{b'\in B_1\cup\bar{B}_1} q_{fb'b} \quad \forall f \in F, b \in B_2 \cup \bar{B}_2 \tag{22}$$

$$\hat{q}_{fb} = \sum_{\pi\in\Pi} \omega_{f\pi b} \quad \forall b \in B, f \in F \tag{23}$$

$$\sum_{f\in F}\sum_{i\in I_1} q_{fib} + \sum_{f\in F} \alpha_f \mu_{fb} \le u_b \quad \forall b \in B_1 \cup \bar{B}_1 \tag{24}$$

$$\sum_{p\in\mathcal{P}} \beta_{f\pi mp}\tau_{\pi bp} + \gamma_{f\pi b} = \omega_{f\pi b} \quad \forall f \in F, \pi \in \Pi, b \in B_m \cup \bar{B}_m, m \in \mathcal{M} \tag{25}$$

$$\sum_{j\in J_m} \vartheta_{\pi bjp} = \tau_{\pi bp} \quad \forall \pi \in \Pi, p \in \mathcal{P}, b \in B_m \cup \bar{B}_m, m \in \mathcal{M} \tag{26}$$

$$\sum_{p\in P}\sum_{b\in B_m\cup\bar{B}_m} \vartheta_{\pi bjp} + \lambda_{\pi j} = D_{\pi j} \quad \forall \pi \in \Pi, j \in J_m, m \in \mathcal{M} \tag{27}$$

$$x_b \in \{0, 1\} \quad \forall b \in \bar{B}_1 \cup \bar{B}_2 \tag{28}$$

$$y_{lb} \in \{0, 1\};\ u_b \ge 0 \quad \forall b \in B_1 \cup \bar{B}_1 \tag{29}$$

$$t_{kb} \in \mathcal{Z}_+;\ v_b \ge 0 \quad \forall k \in K, b \in B \tag{30}$$

$$p_b \in \mathcal{Z}_+;\ w_b \ge 0 \quad \forall k \in K, b \in B \tag{31}$$

$$q_{fib} \ge 0 \quad \forall f \in F, i \in I_{m_1}, b \in B_{m_2} \cup \bar{B}_{m_2}, m_1, m_2 \in \mathcal{M}, m_1 \ne m_2 \tag{32}$$

$$\mu_{fb} \ge 0;\ q_{fbb'} \ge 0 \quad \forall f \in F, b \in B_1 \cup \bar{B}_1, b' \in B_2 \cup \bar{B}_2 \tag{33}$$

$$\tau_{\pi bp} \in \mathcal{Z}_+ \quad \forall \pi \in \Pi, b \in B, p \in \mathcal{P} \tag{34}$$

$$\vartheta_{\pi bjp} \in \mathcal{Z}_+ \quad \pi \in \Pi, b \in B, j \in J, p \in \mathcal{P} \tag{35}$$

$$\theta_{fi} \ge 0 \quad \forall f \in F, i \in I \tag{36}$$

$$\gamma_{f\pi b} \ge 0;\ \omega_{f\pi b} \ge 0 \quad \forall f \in F, \pi \in \Pi, b \in B \tag{37}$$

$$\hat{q}_{fb} \ge 0 \quad \forall f \in F, b \in B \tag{38}$$

$$\lambda_{\pi j} \ge 0 \quad \forall \pi \in \Pi, j \in J. \tag{39}$$

Objective function: The first two terms in (1) represent the fixed cost of adding a foodbank/FRRA to the network and the storage capacity expansion cost at an existing or new Tier-I foodbank. The next three terms correspond to costs for transportation capacity, and staff capacity expansion, respectively, at the new and existing foodbanks/FRRAs. The sixth term captures the cost of procuring the *permitted* food ($\alpha_f = 1$) at a Tier-I foodbank. The next three terms represent flow costs corresponding to (i) donated food from donors to foodbanks/FRRAs, (ii) Tier-I to Tier-II transfers, and (iii) packets from foodbanks/FRRAs to beneficiary nodes. Finally, the last three terms in (1) capture the penalties for *unmet* demand at *beneficiary* nodes, *uncollected* donation at *donor* nodes, and collected but *undistributed* food at *foodbank/FRRA* nodes, respectively.

Constraints: We ensure that at most one of the predetermined storage capacity levels is chosen at an existing (see constraint (2)) or a new (see constraint (3)) Tier-I foodbank. The effective storage capacity (i.e., initial plus expansion) is calculated in (4) and (5) for the existing and new Tier-I foodbanks, respectively. Similarly, effective transport capacities for the existing and new foodbanks/FRRAs of both tiers are presented by (6) and (7), respectively, while (8) and (9) set the upper limits to those transport capacity expansions. In the same manner, while (10) and (11) present the effective staff capacities at the existing and new foodbanks/FRRAs, (12) and (13) set their upper limits. Next, (14) is the donors' supply constraint, while (15), (16) and (17) ensure that the inflow, transfer, and outflow quantities at the foodbanks/FRRAs do not exceed their respective frequency-weighted (i.e., daily vs. weekly) transportation capacities. Similarly, (18) and (19) for the two tiers ensure that the frequency-weighted effective workforce capacities are adequate for handling the net of donation, procurement, and transfer. Constraint (20) represents the workforce requirement for packaging. Constraints (21) and (22) calculate the net food available for distribution at individual Tier-I and Tier-II foodbanks/FRRAs. Eq. (23) handles the allocation of net quantities of different food types to different beneficiary types. Next, (24) is the effective storage capacity constraint for Tier-I foodbanks. With the predetermined compositions to fulfill the nutritional needs of different beneficiary types of both tiers, the total allocated food is packed into beneficiary-specific packets following Eq. (25), and it also captures any collected but unused food (waste) at a foodbank/FRRA. Next, (26)–(27) together enforce the outflow of packets from foodbanks/FRRAs to beneficiaries. The demand constraint (27) also captures the unmet demand of a beneficiary node via the shortage variable $\lambda_{\pi j}$. Finally, (28)–(39) present all the decision variables.

3.3. A numerical illustration

We now present a toy instance along with a solution in Fig. 4 to illustrate how our proposed system works. Tier-I contains Donor 1, an existing foodbank FB_1, a potential foodbank FB_3, and two beneficiary nodes (school with 200 children; old age home with 50 adults). Similarly, Tier-II contains Donor 2, one existing and one potential FRRA ($FRRA_2$ and $FRRA_4$, respectively), and two beneficiary nodes (slum with 50 children, 100 adults; and shelter with 50 adults). While Donor 1 donates 10,000 units of F1, the Donor 2 sends 4500 units of F2 food, while leaving behind 50 units as the uncollected food quantity.

In Fig. 4, each beneficiary node's *weekly demand* (=number of beneficiaries × 7) and unmet demand (in parenthesis) are shown.

An optimal solution of this problem prescribes opening of FB_3 and $FRRA_4$, adding storage capacities at both Tier-I foodbanks, procure F1 type food of 391,000 units at FB_1 and 399,900 units at FB_3, and transfer (follow downward dark arrows) certain amount of F1 from Tier-I foodbanks to Tier-II FRRAs. After all these transfers, the workforce at foodbanks/FRRAs convert the net food (consisting of F1 and/or F2) into P1, P2, or P3 types of packets by following the predefined compositions of F1 and F2 (see Table 4), and then, send those to meet the beneficiaries' demands.

Table 4
Toy example parameters: Tier-I and Tier-II food packet compositions.

Tier-I	PKT 1		Tier-II	PKT 1		PKT 2		PKT 3	
	F1	F2		F1	F2	F1	F2	F1	F2
Child	150	0	Child	350	0	150	150	0	450
Adult	300	0	Adult	400	0	250	250	0	500

4. Case study

We conduct a case study focusing on supply chain network design for the foodbanks and FRRAs operating in Delhi and the National Capital Region (NCR) of India. The choice of the study region is motivated by the fact that India's first foodbank was opened in Delhi in 2012 (The Hindu, 2012), and this region has several foodbanks that can be categorized into two tiers as per our problem setting. Fig. 5 shows the spatial distribution of the donors, foodbanks and FRRAs, beneficiaries of Tier-I & II for the proposed network design at our case study region. We discuss data sources for the case study in Section 4.1, followed by presenting the base model's solution in Section 4.2.

4.1. Data sources

We now discuss how the model parameters for the donor, foodbank/FRRA, and beneficiary node sets, nutritional requirements and food packet composition are arranged for our case study.

Donors: Our study region (see Fig. 5) includes several Tier-I institutional donors (e.g., KFC, Cargill India, Kellogg India, Britannia Industries, Nestle India, ITC, and Hindustan Unilever) that are primarily multinational companies from the FMCG and food industry (India FoodBanking Network, 2023). Tier-II donors primarily include restaurants, small food joints, hostels, office canteens, religious organizations, etc. Obtaining authentic data on the donation quantity and food type from all donors is challenging due to the current ad-hoc nature of foodbank operations that heavily rely on the volunteers' day-to-day availability for donation collection and distribution, lacking enough resources for conducting record-keeping. To resolve this data-collection challenge, we divide our study region into six zones based on the pin codes (ZIP code or postcode equivalent in India) of the institutional donors. Our correspondence with two foodbank personnel from each tier provides us with representative aggregate-level estimates of donation quantities from those zones. Thus, we obtain two sets of donors, six in Tier-I and another six in Tier-II. Furthermore, instead of tracking itemized donation, we consider six food groups, namely, Cereals & millets (grains), Pulses, Dairy & poultry, Fruit & vegetables, Snacks, and Cooked food, that are in compliance with the dietary guidelines issued by National Institute of Nutrition (2011). We present the donation quantities from all donor node in Table 5.

Foodbanks/FRRAs: We identify and classify a total of 15 organizations in our study region as five foodbanks (Tier-I) and 10 FRRAs (Tier-II) that currently operate independent of one another (see Table 6). For the case study, we consider all these 15 entities as *potential* as opposed to *existing* foodbanks/FRRAs since they operate in silos and our model would determine which of those should be selected for inclusion in our proposed integrated network. If a node is selected for inclusion, it can start operating with its existing storage (if it is a foodbank of Tier-I), transport, and workforce capacities as the initial capacities. We, however, anonymize the organizations and add small perturbations in their latitude/longitude data while constructing the potential foodbank/FRRA node-set. To obtain capacity data, we reached out to the foodbanks/FRRAs, however, did not receive reliable information on their effective capacities. One foodbank personnel explained that although they had about 200 registered volunteers, most are irregular, and often the number of 'active' volunteers reduces to single digits.

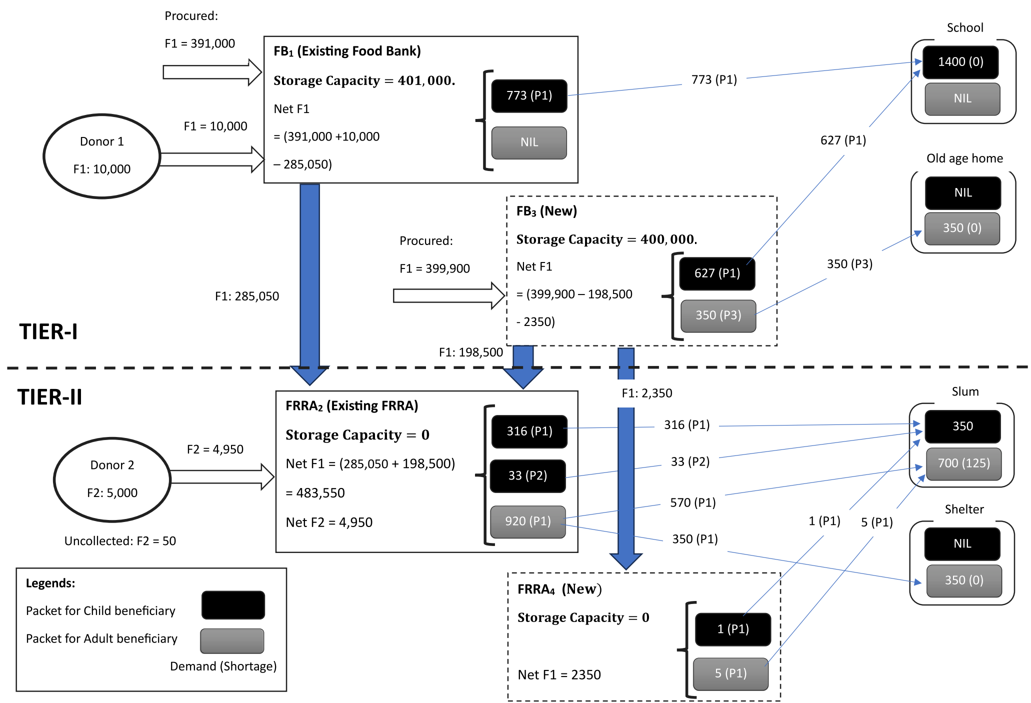


Fig. 4. (Color online) Illustration of a toy problem instance's solution.

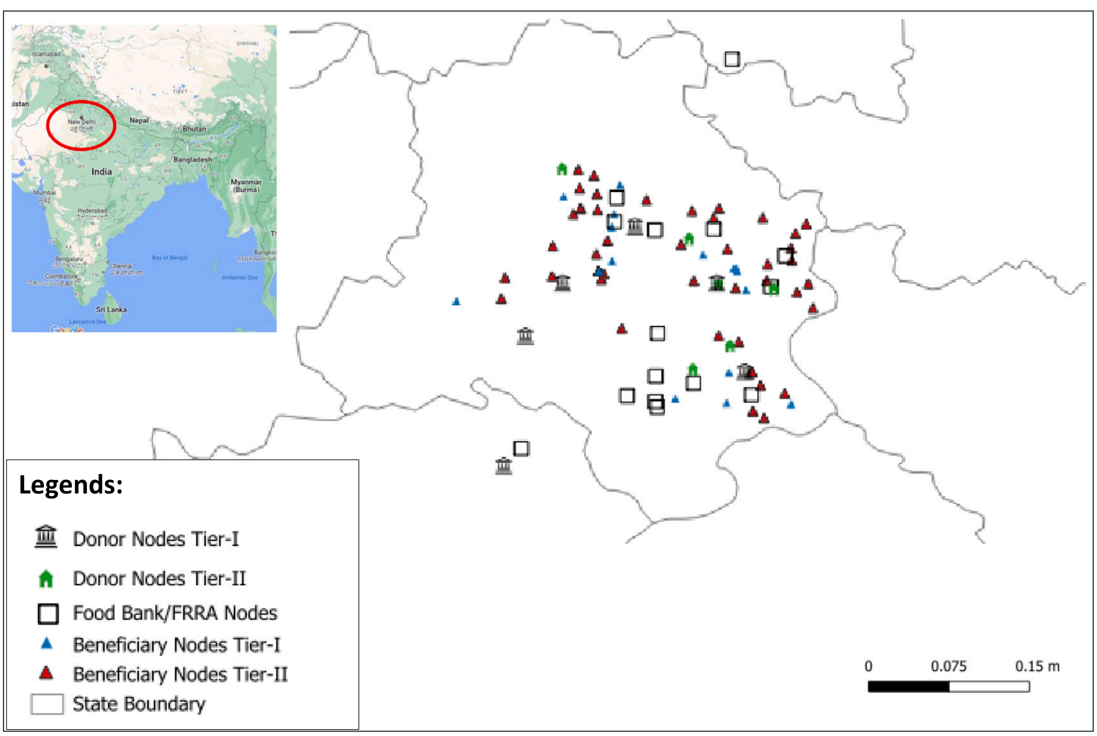


Fig. 5. (Color online) The case study region in Delhi, India.

Table 5
Donation quantities (in Kilograms) of the Donors in Tier-I and II.

Tier-I donors	Cereals & millets	Pulses	Dairy & poultry	Fruit & vegetables	Snacks	Tier-II donors	Cooked food
1	117	114	39	275	142	7	213
2	164	125	58	254	0	8	392
3	234	67	0	0	0	9	704
4	217	78	28	168	171	10	36
5	249	94	119	234	75	11	433
6	–	–	184	219	76	12	223

Table 6
Foodbanks in the study region classified into Tier-I & Tier-II.
Source: IFSA (2023).

No.	Foodbank/FRRA	Website	Specific characteristics	Tier
1	India FoodBanking Network (IFBN)	https://www.indiafoodbanking.org/	Distributes packaged foods	I
2	Mera Pariwar	https://www.meraparivar.org/	Feeds school children	I
3	Delhi Food Banking Network	https://www.responsenet.org/	Foodbank	I
4	SYPM	https://spym.org/	Focus on homeless shelters, accepts surplus food; cold store and logistics available.	I
5	National Organization For Social Empowerment	https://www.nationalngo.org/	Distributes surplus food	I
6	Robin Hood Army	https://robinhoodarmy.com/	Food recovery & redistribution	II
7	Sangarsh India	https://sangharshindia.org/	Food recovery & redistribution	II
8	Roti Bank (AIBRT)	https://www.rotibankdelhi.org/	Food recovery & redistribution	II
9	Feeding India	https://www.feedingindia.org/	Food recovery & redistribution	II
10	Ashray Adhikar Abhiyan	https://www.homelesspeople.in/	Food recovery & redistribution	II
11	Indian Roti Bank	https://www.rotibank.co.in/roti-bank-in-delhi/	Food recovery & redistribution	II
12	Jeevan Hi Udeshya	https://www.facebook.com/jeewanhiudeshya/	Food recovery & redistribution	II
13	Project Jeevan	https://indianlocalfoods.com/ngo-for-food-donation-in-india/	Food recovery & redistribution	II
14	Khana Daan	https://www.facebook.com/daanthali/	Freshly cooked food	II
15	Little India Foundation	https://little-india-foundation.business.site/	Food recovery & redistribution; cooking	II

Table 7
Initial capacity estimates of the potential foodbanks/FRRAs.

Tier (entity)	Initial capacity			
	Storage	Transport	Volunteers	Staff
I (Foodbank)	1000 kg	1000 kg	5	2
II (FRRA)	–	200 kg	5	2

With some realistic inputs, we estimate the initial capacities of the potential foodbanks as shown in Table 7.

Beneficiaries: We consider 76 beneficiary locations in our study region, out of which 16 are categorized as Tier-I and the remaining 60 as Tier-II. While Tier-I locations include schools, child welfare centers, and old age homes, Tier-II locations represent certain areas with underprivileged populations, e.g., slums, shelters, immigrant neighborhoods, etc. Considering the significant difference in the nutritional requirement of children and adults, and the higher socio-economic vulnerability of Tier-II beneficiaries, we create four distinct beneficiary types, specifically, child at Tier-I, adult at Tier-I, child at Tier-II, and adult at Tier-II. Estimating the demand of Tier-I beneficiaries is relatively straightforward from their institutional enrollment records. However, for the Tier-II beneficiary nodes, as we obtained aggregate level demand estimates through correspondence with foodbank personnel, to ensure a consistency in parameter estimation, we assumed that the numbers of child and adult beneficiaries in Tier-II were in the proportion of 44.3% and 55.7%, respectively, following these age groups' representation in the Census of India (2011). Then, for the Tier-II beneficiary nodes, we multiplied their population with these percentages to obtain the estimate of each beneficiary type, as presented in Table 8.

Nutrition-related data: Following the dietary guideline from National Institute of Nutrition (2011), we show the nutritional requirements of different beneficiary types in Table 9, with the purchase price of each food group obtained from AgMarkNet (2023). These nutritional requirements are considered in full (i.e. 100%) for the more vulnerable Tier-II beneficiaries, as they require extensive support in terms of all meals per day. However, since Tier-I beneficiaries receive this support in the form of a supplement to the primary nutrition from their institutions (e.g., school, care home, etc.), we set their requirements at 50% of the values shown in Table 9.

Packet types: With guidance from the nutritional requirements data (National Institute of Nutrition, 2011), we consider three food packet types (see Table 10) that are made from the heterogeneous mix of uncooked and cooked food donations. Note, these packet types differ in the proportion of cooked food ranging from 0% (packet type 1) to 100% (packet type 3). Packet type 1 consists of only the foods with extended shelf-life, raw, ready-to-cook/eat type items, received as donations or procured at Tier-I. As per our problem setting, since no donation from Tier-II (containing cooked food) enters the Tier-I flow, the beneficiaries of Tier-I receive only packet type 1. However, a Tier-II beneficiary can receive any of the three packet types. Packet type 2 is a mix of both tiers' donations, therefore, the nutritional requirements given in Table 9 for each food group, have been halved. Finally, packet type 3 covers a beneficiary's daily nutritional need entirely with cooked food received as donation at Tier-II.

Miscellaneous parameters: Apart from those discussed above, our model uses several other capacity-, cost-, and logistics-related parameters. Table 11 lists them along with their sources for estimation, wherever possible.

4.2. Base model solution

With parameter settings as explained in Section 4.1, we solve the case study problem instance. This solution, referred to hereafter as the 'base case', suggests five Tier-I foodbanks (at nodes 1, 2, 3, 4, 5) and three Tier-II FRRAs (at nodes 9, 10, 13) to include in the integrated network. Tables 12 and 13 present the base case solution, illustrating capacity and flow decisions, respectively.

In Tier-I, except for one out of the five foodbanks, all others need storage capacity extensions (three at their highest levels). FRRAs have no storage capacity, as per our problem setting (shown by '–' in Table 12). A significant workforce extension is observed at almost all Tier-I foodbanks (totaling 246 persons), compared to Tier-II FRRAs (25 persons), because Tier-I foodbanks require a larger workforce to handle *weekly inflows* of donated and procured bulk foods (packing and distribution are done daily). On the other hand, Tier-II FRRAs handle *daily inflow* (donations at Tier-II plus transfers from Tier-I), packaging, and distribution, thereby requiring less workforce. No transportation capacity addition is needed at Tier-I foodbanks but up to two vehicles of different capacities are deployed at all the three chosen Tier-II FRRAs. Although Tier-I is involved in large quantities of food purchases, as

Table 8
Estimated population of different beneficiary types in Tier-I & II.

Tier	Beneficiary locations	Number of locations	Total beneficiary count		
			Child	Adult	Total
I	Schools and Child welfare centers	12	6377	–	6377
	Old age homes	4	–	594	594
II	Slum, Shelter, and other underprivileged areas	60	5058	6353	11,411
Total		76	11,435	6947	18,382

Table 9
Beneficiary-wise food requirements and purchase prices.

Food group	Gm/portion		Recommended Portion		Total Requirement (gm)[a]		Price (₹/kg)
	Child	Adult	Child	Adult	Child	Adult	Source: AgMarkNet (2023)
Cereals, millets	30	30	10	15	300	450	30
Pulses	30	30	2	2.5	60	75	140
Dairy, poultry	100	100	5	3	500	300	50
Fruit, vegetables	100	100	5	6	500	600	90
Snacks (sugar, fat)	5	10	15	5	75	50	100

[a] For Tier-I, take 50% of these values; for Tier-II take as-is.

Table 10
Configuration of food packets (all figures are in gms).

Food group	Packet type 1		Packet type 2		Packet type 3	
	Child	Adult	Child	Adult	Child	Adult
Cereals & millets	300	450	150	225	**0**	**0**
Pulses	60	75	30	37.5	**0**	**0**
Dairy & poultry	500	300	250	150	**0**	**0**
Fruit & vegetables	500	600	250	300	**0**	**0**
Snacks (sugar & fat sources)	75	50	37.5	25	**0**	**0**
Cooked	**0**	**0**	717.5	732.5	1435	1465

Table 11
Estimation of miscellaneous model parameters.

Parameter	Specifics	Capacity	Cost (₹)	Comment/ Source
Storage level	Small	2000 kg	15,000	https://www.99acres.com/
	Large	6000 kg	40,000	
Transport	Car	200 kg	5250	Wagon-R, a commonly used vehicle for such transport job in the study region, has cargo capacity around 400 kg (source: https://www.car.info/). Giving volumetric allowance, we assume half of its capacity. Cost of renting: realistic assumption.
	Truck	700 kg	14,000	Capacity: https://trucks.cardekho.com/. Cost of renting: realistic assumption.
Workforce	Donation handled per person	100 kg	3500 per person per week	In India ₹500 is approx daily minimum wage. (Source: https://www.india-briefing.com/news/guide-minimum-wage-india-2023--19406.html/)
	Packets handled/person/week	1000 packets		Estimated based on correspondence with foodbank staff.
Cost of adding new foodbank/FRRA			10,000	Cost incurred due to miscellaneous initiatives, e.g., advertising, office setup, utilities etc.

delivery of those is managed by sellers, foodbanks need not increase transportation capacity to handle bigger purchases.

Table 13, presenting the flow decisions, is organized into two parts. The supply side (left) shows flows of donated, purchased, and transferred food within and between the two tiers. The column 'Net for Distribution' represents the total amount of food available at a foodbank/FRRA for distribution to the downstream beneficiary nodes over a week's span. As per our base model parameters, Tier-II with more beneficiaries, handles around 16.5 thousand kilograms of food, in comparison with about 10 thousand kilograms in Tier-I. The demand side (right) of Table 13 provides a breakup of different packet types in two tiers. Note that the total number of packets 18,382 (=6971 + 11,411) matches the total number of beneficiaries in each tier (see Table 8), i.e., no shortage occurs.

5. Numerical analysis

To better understand the effects of demand and donation (supply) changes, we undertake three experiments by systematically varying demand, donation, and both. We discuss the main observations and insights in Sections 5.1–5.5. Moreover, we observe the effects of adding a total budget constraint in Section 5.7, and linked with that, a constraint enforcing strategic-to-operational cost ratio in Section 5.8. We discuss different equity considerations and their effects on the solution in Section 5.9.

Table 12
Base case solution: capacity decisions.

Tier-I Foodbanks	Storage (gm)		Transport (gm)		Workforce (# persons)	
	Initial	Extension (level)	Initial	Extension	Initial	Extension
1	1,000,000	0	1,000,000	0	7	3
2	1,000,000	6,000,000 (**large**)	1,000,000	0	7	63
3	1,000,000	6,000,000 (**large**)	1,000,000	0	7	63
4	1,000,000	2,000,000 (small)	1,000,000	0	7	23
5	1,000,000	6,000,000 (**large**)	1,000,000	0	7	59
	$\sum$ = 25,000,000		$\sum$ = 5,000,000		$\sum$ = 246	
Tier-II FRRAs	Storage (gm)		Transport (gm)		Workforce (# persons)	
9	–	–	200,000	900,000 (1 car, 1 truck)	7	3
10	–	–	200,000	700,000 (1 truck)	7	1
13	–	–	200,000	400,000 (2 cars)	7	0
			$\sum$ = 2,600,000		$\sum$ = 25	

Table 13
Base case solution: flow decisions.

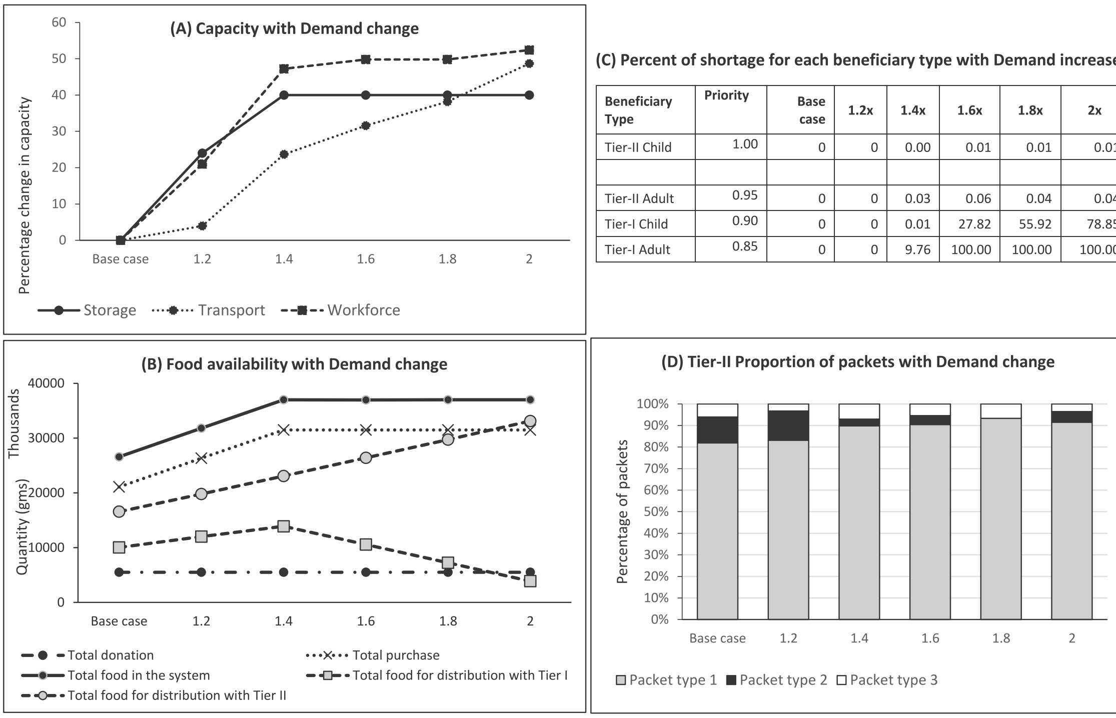
	Supply side: Flow of food items (in gms.)					Demand side: Packet (#)			
	Donation (in)	Purchase (in)	Transfer (out) to Tier-II	Transfer (in) from Tier-I	Net for Distribution	PKT 1	PKT 2	PKT 3	Total PKT
Tier-I FB									
1	799,000	201,000	1,240	–	998,760	0	511	185	696
2	687,000	6,313,000	70	–	6,999,930	9	4868	1	4,878
3	472,000	6,513,580	5,770,970	–	1,214,610	674	80	80	834
4	942,000	2,058,000	3,000,000	–	0	0	0	0	0
5	601,000	5,999,000	5,792,095	–	807,905	1	0	562	563
					10,021,205				6,971
Tier-II FRRA									
9	0	–	–	6,905,770	6,905,770	4738	0	0	4,738
10	994,545	–	–	4,604,925	5,599,470	2484	1374	0	3,858
13	1,006,455	–	–	3,053,680	4,060,135	2128	0	687	2,815
					16,565,375				11,411

5.1. Experiment 1: effects of demand increase

Since in real life most foodbanks face the issue of meeting demand with limited supply, we study the effects of demand increase. To this end, we systematically increase demands of all beneficiary nodes of both tiers in steps of 20%, while keeping donation quantities from all the donors unchanged. Exhibits (A) to (D) of Fig. 6 show these steps as 'Base case', followed by '1.2x', '1.4x', …, '2x', representing beneficiaries' demand increase by 20%, 40%, …, 100%. Fig. 6(A) illustrates the capacity increase in storage, transport, and workforce categories due to a strain in the system triggered by a demand increase. However, the changes are not linear and dissimilar for different capacity categories in our case study parameter settings. While the '1.2x' case causes an approximate 20% increase in both storage and workforce capacities, less than 5% transport capacity addition is observed. Case '1.4x' and beyond, no further storage capacity increase occurs. At this point, with all five Tier-I foodbanks forced to operate with their maximum possible level of storage capacities, storage capacity becomes the bottleneck. Transportation and workforce capacities increase, however, at slightly different rates as the beneficiary demand further increases. Fig. 6(B) represents the system-wide food availability through donations and purchases. While donation quantities are kept fixed, food purchase increases at Tier-I to satisfy the rising demand. However, as procured food needs storage, whose capacity becomes the bottleneck at the '1.4x' case, the food purchase level becomes constant as demand further increases. This also explains why shortage is observed at this level and with further demand increase since procurement increase no longer helps. Furthermore, two diverging lines in Fig. 6(B), showing the changes in food availability at Tier-I and Tier-II foodbanks and FRRAs respectively, illustrate some interesting aspects of sharing limited food between two tiers. Note that with the same demand increase, Tier-II receives a higher share of available food (steady increase) while the Tier-I receives less (steady decrease after '1.4x' case). This is primarily dictated by the higher priorities for the Tier-II beneficiaries compared to their Tier-I counterparts (see Fig. 6(C)). With demand increase and donations remaining unchanged, the shortage profile expressed as percentages of the total number of beneficiaries in each of the four types (i.e., Tier-I child, Tier-II adult, etc.), is presented in Fig. 6(C). As discussed above, no shortage occurs at '1.2x', and thereafter, it gradually increases while obeying the relative priorities of different beneficiaries. Hence, almost 99.99% of Tier-II children's demands are met in all cases up to '2x'. On the other hand, the needs of adults in Tier-I remain totally unmet from the '1.6x' case. A similar pattern is observed for the children of Tier-I, however, due to their priority weight of 0.90, unlike the adults, their shortage remains around 79% even in the '2x' case. We summarize this as a key observation below.

Key observation 1: *In the absence of any budget constraint, demand increase can be handled by an increase in procurement and different capacity additions up to a point, after which Tier-I foodbanks' storage capacities become bottleneck, and shortage is observed as per relative priorities of the beneficiary types.*

As demand increases to '1.6x' and above, despite shortages, part of the available donation is not collected from Tier-II donors, and *penalties for both shortage and uncollected food* are charged. This interesting phenomenon occurs because demand satisfaction is not linearly related to the donation quantity, it rather depends on the compositions of packet types (see Table 10), and, in turn, the nutritional content of the donated food. With demand increase, our previous observation on the increase in purchase (essential to meet nutritional needs) until the Tier-I foodbank's storage capacity is exhausted (see Fig. 6(B)), explains leaving some donated food as uncollected at Tier-II donor sites even when there are shortages in the system. Fig. 6(D), showing the increased proportions of packet type 1 at Tier-II with increasing



Beneficiary Type	Priority	Base case	1.2x	1.4x	1.6x	1.8x	2x
Tier-II Child	1.00	0	0	0.00	0.01	0.01	0.01
Tier-II Adult	0.95	0	0	0.03	0.06	0.04	0.04
Tier-I Child	0.90	0	0	0.01	27.82	55.92	78.85
Tier-I Adult	0.85	0	0	9.76	100.00	100.00	100.00

Fig. 6. Effects of demand increase.

demand further highlights the importance of considering nutritional aspect in the decision-making process. Although donation quantity remains unchanged at Tier-II, its relative contribution (low shelf-life food) gradually reduces with the demand increase. Therefore, food collected and purchased at Tier-I, being nutritionally more significant and the major composition of packet type 1, largely contributes in Tier-II's demand fulfillment.

Key observation 2: *After one level of demand increase, the increased procurement at Tier-I forces making more of packet types 1 and 2, following their predetermined compositions. Consequently, donation at Tier-II becomes less important, leaving them partly uncollected.*

5.2. Experiment 2: effects of donation change

To observe the effects of donation quantity change, we conduct an experiment where donations in both tiers are systematically changed (increased or decreased) from the base case values in steps of 20%. No change is made in demand or other model parameters.

As donation varies, interesting changes in different capacities are captured in Fig. 7(A). Observe that storage capacities are insensitive to changes in donation between '0.8x' and '1.6x'. With donation decrease '0.6x' or below, purchase increases to compensate for the shortfall, thereby increasing the storage requirement in Tier-I. In donation increase of '1.6x' and above, (which includes Tier-II donation as well, requiring no storage) we observe a gradual decrease in storage requirement. A similar pattern is observed for workforce capacity. However, transport capacity changes in the other way: after a 40% donation increase, more capacity is needed to collect the increased donation at both tiers and to conduct the Tier-I to Tier-II transfers. Beyond '2x' donation increase, we observe uncollected donations (not shown in exhibits), therefore, do not explore further.

Fig. 7(B) depicts the changes in food donation and purchase quantities, and availability in each tier and in the system. We observe a linear decrease in purchases as donations increase, keeping the total quantity unchanged. Also, Fig. 7(C) shows that donation increase causes a small decrease in strategic cost (foodbank opening and capacity building) and a significant decrease in the operational cost (transport and purchase). While an increase in donation at both tiers reduces the system-wide purchase requirement (operational cost savings), some strategic cost savings occur. With the increase in Tier-II's donation, the dependency on Tier-I is relieved to some extent, which, in turn, reduces Tier-I's storage requirements, thereby, saving on the strategic cost. In our case study's parameter setting, no shortage is incurred at any of the cases between '0x' - '2x', because a donation decrease is always compensated by increased purchase at Tier-I. Fig. 7(D) provides interesting observations about packet composition change in Tier-II with the changes in donation. In the extreme case of zero donation, only Packet Type 1 is formed from all the procured food at Tier-I. As donations increase at both tiers, Packet Types 2 and 3 are also made with the cooked/ready-to-eat food donation received at Tier-II. However, this leads to a key observation with a practical recommendation as follows.

Key observation 3: *Although packet type 1 with the highest proportions of uncooked food can be instrumental in addressing demand increase via additional procurement at Tier-I, it would pose practical issues to the poorest Tier-II beneficiaries without provisions for self-cooking at shelters. For those, packet types 2 and 3, reducing the challenges of on-site cooking and feeding by limited foodbank volunteers, would be preferred. Therefore, initiatives for encouraging cooked or ready-to-eat food donation from Tier-II donors can help in reducing the pressure on Tier-I as well as the integrated system.*

5.3. Experiment 3: simultaneous donation decrease and demand increase

The joint effects of donation decrease and demand increase are studied by changing both parameters simultaneously in steps of 20% (e.g., demand '1.2x' and donation '0.8x'). Although the pattern of changing food availability is similar to Fig. 6(B), we note that to compensate for the donation decrease in both tiers, the purchase quantity in Tier-I does not increase proportionately because the storage capacity of Tier-I foodbanks becomes bottleneck at demand '1.4x' and donation '0.6x' (similar to Experiment 1). Additionally, as shown in

Table 14
Percent of shortage for each beneficiary type in Experiment 3.

Beneficiary type	Priority	Multipliers (Demand, Supply)					
		Base case	(1.2x, 0.8x)	(1.4x, 0.6x)	(1.6x, 0.4x)	(1.8x, 0.2x)	(2x, 0x)
Tier-II Child	1.00	0	0	0	0.04	0.03	0.01
Tier-II Adult	0.95	0	0	0	0.03	0.03	0.02
Tier-I Child	0.90	0	0	0	36.01	65.65	89.79
Tier-I Adult	0.85	0	0	**76.02**	**100.00**	**100.00**	**100.00**

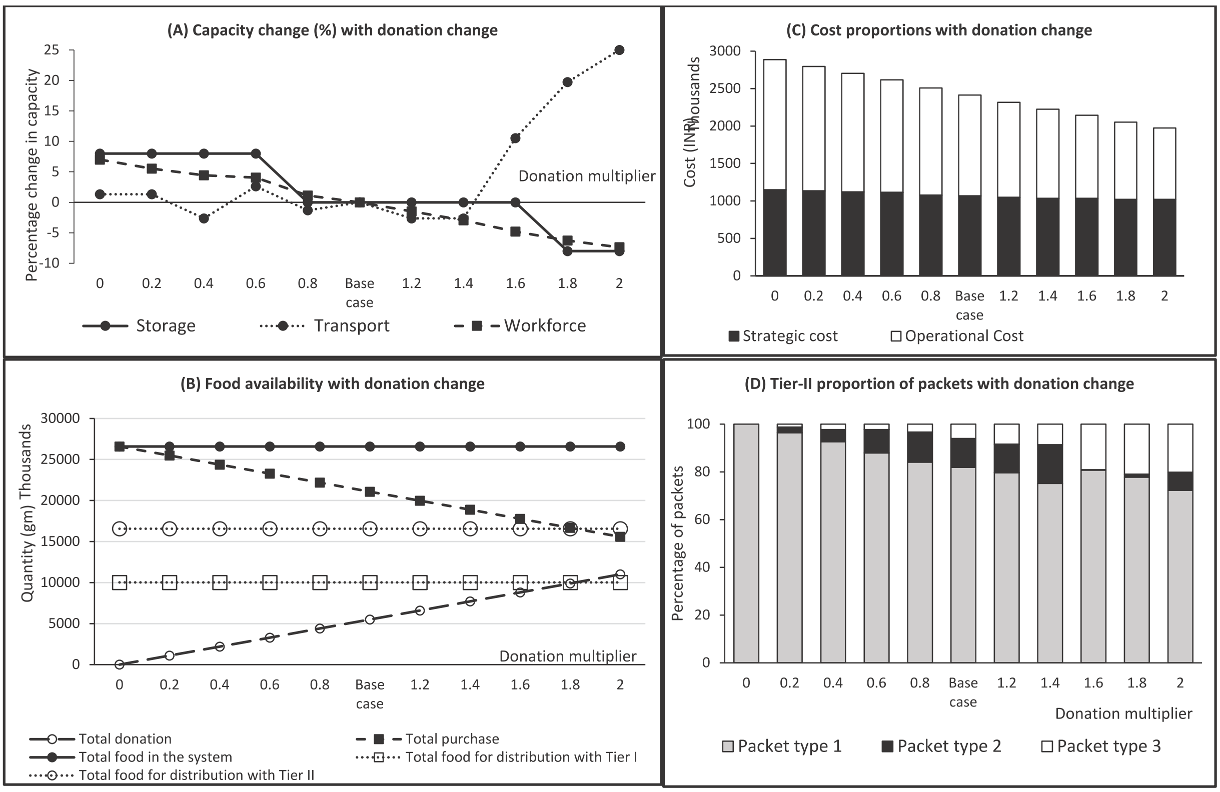


Fig. 7. Effects of donation change (increase and decrease from Base case).

Table 14, demand increase triggers shortage at this point to a much higher extent compared to Experiment 1. Specifically, shortages in Tier-I adults aggravate sharply (shown in boldface) from the '1.4x demand, 0.6x supply' case.

Foodbanks and FRRAs opened in Experiment 1-3: The systematic change in demand and donation quantities made in experiments 1–3 influences the network structure as presented in Table 15. In Experiment 1 (donation constant), Tier-I procurement increases to satisfy the growing demand. The need for more storage to accommodate this increased food has forced more foodbanks to open, mostly with their highest levels of storage capacities. In Experiment 2, to compensate for donation change, a systematic adjustment occurs in purchase quantity. Since demand stays the same, the storage need is also unchanged, keeping the same eight foodbanks/FRRAs open in all the cases we present. In Experiment 3, we observe a gradual increase in the number of foodbanks, all operating at their highest levels of storage capacities (similar to Experiment 1), to accommodate the increased purchases compensating for the donation decrease.

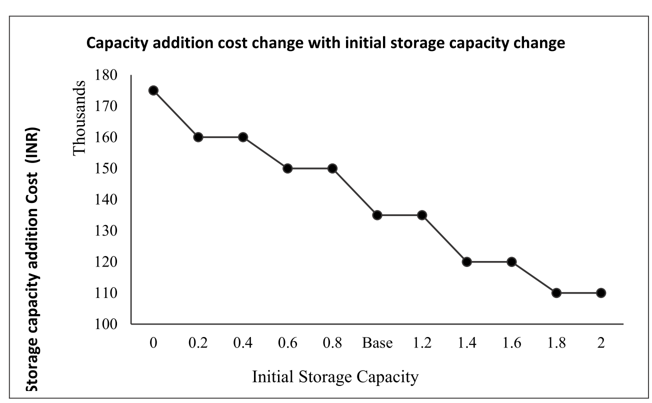


Fig. 8. Effects of changing initial storage capacity of Tier-I foodbank (S_b^0).

5.4. Experiment 4: effects of changes in initial capacity related parameters

As presented in Table 11, the values of several capacity related parameters such as initial storage capacity (S_b^0), initial transport capacity (T_b^0), the initial numbers of volunteers (V_b^0) and paid stuff (ρ_b^0) are estimated based on anecdotal evidences and discussions with the foodbank personnels. Therefore, it is worth investigating the effects of changing these parameters on the solution from their estimated values by conducting a systematic sensitivity analysis.

To observe the effect of changing initial storage capacities of the Tier-I foodbanks, similar to the previous experiments, we make the cases '0x' to '2x' of the base value S_b^0; $b \in B_1 \cup \bar{B}_1$. For simplicity, we change S_b^0 values for all Tier-I foodbanks in the same manner.

Table 15
Number of opened foodbanks in experiments 1–3.

Experiment 1: demand increase, donation same						
Demand multiplier	Base case	1.2x	1.4x	1.6x	1.8x	2x
# Foodbanks/FRRAs	8	8	12	13	13	14
Experiment 2: donation increase, demand same						
Donation multiplier	Base case	1.2x	1.4x	1.6x	1.8x	2x
# Foodbanks/FRRAs	8	8	8	8	8	8
Experiment 3: donation decrease, demand increase						
Demand multiplier	Base case	1.2x	1.4x	1.6x	1.8x	2x
Donation multiplier	Base case	0.8x	0.6x	0.4x	0.2x	0x
# Foodbanks/FRRAs	8	9	9	13	13	14

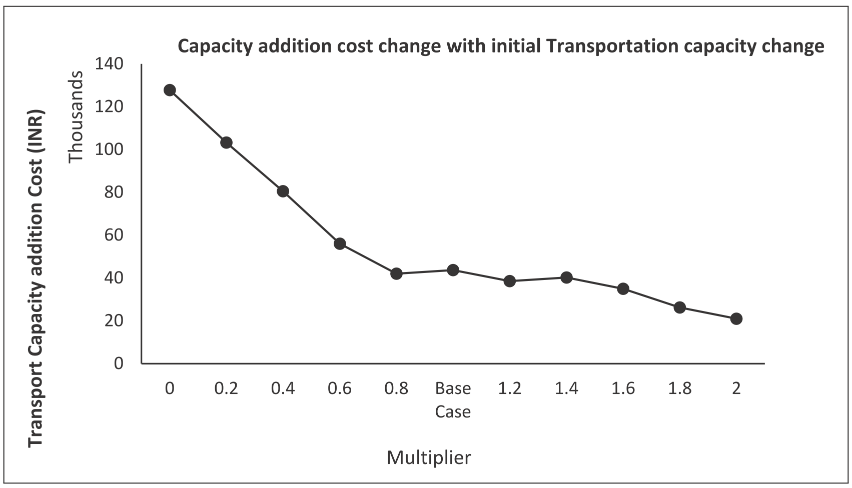


Fig. 9. Effects of changing initial transport capacity of foodbank (T_b^0).

Fig. 8 presents the corresponding changes in storage capacity addition cost. Our experiment shows that the lower the initial storage capacity at the (Tier-I) foodbanks, the higher the capacity addition cost. Thus, in '0x' case (no initial capacity), the highest capacity installation cost is incurred. Note that due to the discrete nature of storage capacity addition choices (i.e., S_l), the change in the storage capacity addition cost shows a stepwise pattern. Moreover, we observe in the case study parameter setting that the capacity addition cost is more significant when S_b^0 is less than the 'Base case' as compared to the higher capacity cases. For example, in '0.4x' case (initial storage capacity 60% less than 'Base') incurs ((160-135)/135 × 100%=) 18.5% more storage capacity addition cost than the 'Base' case. On the other hand, in the '1.6x' case where the initial storage capacity is 60% more than the 'Base case', we observe that the storage capacity addition cost decreases only by ((135 - 120)/135 × 100%=) 11.1%. However, no significant change is observed in terms of network configuration, flows, transport and workforce capacities with the change in S_b^0.

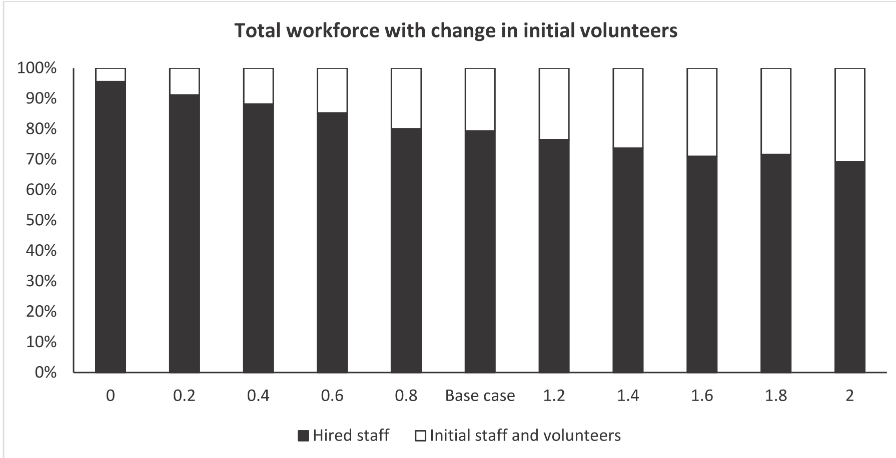
A very similar pattern is observed when T_b^0, the initial transportation capacity at the foodbanks is varied gradually. Fig. 9 shows that the transport capacity acquisition costs are more striking when T_b^0 is low. Having a larger transportation capacity, however, does not affect the solution significantly because the flow through foodbank network remains constant. Also, this change does not influence the network structure, storage and workforce capacities requirements either.

Next, to understand the effects of change in the initial numbers of volunteers (V_b^0) and paid staff (ρ_b^0) at the foodbanks, we vary the initial number of volunteers and staff independently (case '0x' to '2x'). As shown in Fig. 10, in our case study parameter setting, although the total workforce size remains almost constant, its composition changes significantly. Specifically, when initial numbers are small, hiring is considerably high at the foodbanks for continuing the activities. In the case '0x' (an extreme situation) with $V_b^0 = 0$ at all foodbanks, as high as (258/270 × 100%=) 96% of the new staff get hired. In the other extreme, i.e., the '2x' case, the number of staff hired reduces to (189/273 × 100%=) 69% of the workforce. This change is also reflected in the workforce-related cost incurred. In all the cases '0x' – '2x', the optimal solution prescribes operating all the five Tier-I foodbanks, and mostly three Tier-II foodbanks (out of 5 and 10 candidates for the respective tiers). Interestingly, with a similar systematic changes in the initial number of staff (ρ_b^0) while keeping V_b^0 values unchanged, we do not observe any significant impact on the workforce composition. The number of new staff hiring stays around 80% throughout the variation from '0x' to '2x' cases, however, one difference from the above experiment (varying initial number of volunteers) is observed in the network configuration. Although all the five Tier-I foodbanks are opened in '0x' to '2x', more Tier-II foodbanks are opened when the initial staff is below the 'Base case' (i.e., '0x' to '0.8x'). From the above analyses, we make the following key observation.

Key observation 4: *With the increase in initial capacity (storage, transportation, and workforce) at foodbanks, the respective capacity addition costs, thereby, the total cost of designing and operating the network gets reduced. Specifically, in our case study setting, between the initial number of volunteers and staff, the former becomes a key factor from the capacity perspective.*

5.5. Experiment 5: effects of changing penalties

In the objective function of model [P], we use three penalty terms $P_m^{(1)}$, $P_m^{(2)}$, and $P_{\pi m}^{(3)}$ to discourage uncollected food donations (waste at donor sites), collected but unused donation (waste at foodbank sites), and unmet demand (shortage at beneficiary site), respectively. Unlike other cost components in objective function (1) of model [P], these three penalty terms represent *notional* costs. To discourage wastes and



Multipliers: =	0	0.2	0.4	0.6	0.8	Base	1.2	1.4	1.6	1.8	2.0
Initial staff & volunteers	12	24	32	40	54	56	64	72	80	77	84
Hired staff	258	246	238	231	217	215	208	201	196	194	189
Total workforce size	270	270	270	271	271	271	272	273	276	271	273

Fig. 10. Effects of changing initial number of volunteers (V_b^0).

shortages in the base model solution, we set very high values for these penalties. Now, to perform sensitivity analysis, we run first part of our experiment to understand the possible effects of systematically varying the penalty values one at a time in the range of '0x' to '2x' of their baseline values. Then, from our observation, we conduct a second part of the experiment to understand the possible impact of simultaneously varying these penalties.

From the first part of the experiment, we understand that any difference in the solution occurs only when any of these three penalties is set to 0, otherwise, even a small penalty value leads to the same base solution. Specifically, for $P_m^{(1)} = 0$, we observe that Tier-I donation remains unchanged as of the base case, however, Tier-II donations slightly reduce (some donations are not collected), and the shortage is fulfilled by additional purchase of food items with the required nutritional values. Nevertheless, in our parameter setting, this uncollected donation quantity is less than 0.1% of the total food inflow. We make similar observations by setting $P_m^{(2)}$ to zero. Specifically, some small quantity of cooked food donation is collected from the donors by the FRRA (to avoid penalty $P_m^{(1)}$), but eventually it is not distributed. Setting $P_{\pi m}^{(3)}$ to zero causes unmet demands for 34.8% of children and 0.5% of Adults in Tier-I, and for 74.7% of children and 59.5% of Adults in Tier-II. The only demand fulfillment in this scenario is due to mandatory collection and utilization of donations and no other food procurement takes place.

We now conduct the second part of the experiment, where penalties are varied *simultaneously*. For this, informed by the above observations, we set the penalties to 0 and 1 only, i.e., a total of 8 combinations of ($P_m^{(1)}$, $P_m^{(2)}$, $P_{\pi m}^{(3)}$), and present the outcomes in Table 16, from which some interesting observations can be made. First, observe that in rows 1 and 3 of Table 16, as no penalty is charged for not collecting donations and for shortages, the optimal solution prescribes to leave 100% of the donations uncollected, leading to 100% shortages at both tiers for both adults and children. Since no collection is made, therefore there is no "collected but unused food" at the foodbanks or FRRAs, as indicated by "N/A" in those rows. With ($P_m^{(1)}$, $P_m^{(2)}$, $P_{\pi m}^{(3)}$) = (1, 0, 0), all donations are collected to avoid $P_m^{(1)}$, but that do not get distributed to the end beneficiary, because in the absence of penalizing the unmet demand, that is the best decision to avoid incurring logistical costs downstream. However, in row 2, with ($P_m^{(1)}$, $P_m^{(2)}$, $P_{\pi m}^{(3)}$) = (0, 0, 1), almost all donations are collected and distributed to satisfy all beneficiaries' demands in order to avoid incurring shortage penalties. This shows $P_{\pi m}^{(3)}$ is dominant over the other two penalties, as further evidenced by the penalty combinations (0, 1, 1), (1, 0, 1), and (1, 1, 1), all leading to 0% shortages for all beneficiary types since $P_{\pi m}^{(3)}$ is set to 1. Finally, in row 7, ($P_m^{(1)}$, $P_m^{(2)}$, $P_{\pi m}^{(3)}$) = (1, 1, 0) causes all donations to be collected and distributed, however, all beneficiaries experience shortages, which is already discussed in the first part of this experiment.

From the above experiments with penalty values, we make the following key observation.

Key observation 5: *In case study parameter setting, the solution is robust to the penalty value changes unless some or all the penalties are completely removed. Among the three penalties, the penalty for shortage plays the dominant role in ensuring adequate flow through the foodbank network to satisfy the end beneficiaries' demands.*

5.6. The value of integration

The discussion on the effects of demand and donation variations in Sections 5.1–5.3 would help in appreciating the value of integration of the two tiers in our proposed network. For a quantitative understanding, we cut the connection between two tiers by fixing all transfer variables $q_{fbb'}$ to zero, and re-solve our model for (i) base case, and (ii) simultaneous demand increase and donation decrease. In (i), we observe a 40%, 26%, and 55% decrease in storage, transport, and workforce capacities, respectively, from the base case solution. Clearly, the disintegrated system – having Tier-II FRRAs with no storage capacities – requires much less of total capacity than the integrated one, and incurs 65% less cost (excluding penalties). However, in the absence of the integrated system's transfer mechanism, as opposed to 'no shortage' in the base case of the integrated setting, Tier-II of the disintegrated system exhibits a staggering shortage of 72.5% and 100% of child and adult beneficiaries, respectively. The shortage worsens under the Experiment 3 setting (simultaneous demand increase and donation decrease) as shown in Table 17, and a comparison with Table 14 entries would emphasize the value of integration.

5.7. Adding budget constraint

While our proposed model [P] without a budget constraint, determines the (baseline) cost for establishing an integrated foodbank network, understanding the impact of a tight budget can be valuable to a decision-maker. To better understand this, we add a simple budget

Table 16
Scenario analysis on different penalty values.

Penalty combinations			Uncollected (%)		Collected but unused (%)		Shortage (%)			
$P_m^{(1)}$	$P_m^{(2)}$	$P_{\pi m}^{(3)}$	T-I	T-II	T-I	T-II	T-I Child	T-II Child	T-I Adult	T-II Adult
0	0	0	**100**	100	N/A	N/A	**100**	**100**	**100**	**100**
0	0	1	0	0.13	0	0	0	0	0	0
0	1	0	**100**	**100**	N/A	N/A	**100**	**100**	**100**	**100**
0	1	1	0	3.54	0	0	0	0	0	0
1	0	0	0	0	**100**	**100**	**100**	**100**	**100**	**100**
1	0	1	0	0	0	0.001	0	0	0	0
1	1	0	0	0	0	0	34.8	74.8	0.5	59.5
1	1	1	0	0	0	0	0	0	0	0

Table 17
Shortage % with demand increase and donation decrease in disintegrated system.

Beneficiary type	Priority	Multipliers (Demand, Supply)					
		Base case	(1.2x, 0.8x)	(1.4x, 0.6x)	(1.6x, 0.4x)	(1.8x, 0.2x)	(2x, 0x)
Tier-II Child	1.00	72.47	81.55	88.16	93.11	96.94	100
Tier-II Adult	0.95	100.0	100	100	100	100	100
Tier-I Child	0.90	0	0	0.01	0.02	0.01	0
Tier-I Adult	0.85	0	0	0.12	0	0.19	0

Table 18
Budget sensitivity analysis.

Network	Budget multipliers:=	0x	0.2x	0.4x	0.6x	0.8x	Base case
	No. of foodbanks/FRRAs	0	6	6	7	7	8
Capacity	Storage (kg)	0	7000	13,000	17,000	21,000	25,000
	Transportation (kg)	0	5900	6100	6500	6800	7600
	Workforce (#)	0	78	126	174	222	271
Shortage (%)	Tier-II Child (1.0)	100	13.2	3.6	0	0	0
	Tier-II Adult (0.95)	100	100	99.9	80.2	42.6	0
	Tier-I Child (0.9)	100	71.8	28.1	2.7	0	0
	Tier-I Adult (0.85)	100	100	100	100	35.7	0
Costs	Strategic (%)	0	53.3	48.8	45.7	44.7	44.1
	Operational (%)	0	46.7	51.2	54.3	55.3	55.8

constraint by restricting total cost to an upper bound B, whose initial value is set as the sum of strategic and operational costs obtained from the base case solution. Next, this B value is gradually tightened by multiplying its initial value with 0.8, 0.6, …, 0, and the model is re-solved every time. In our case study's parameter setting, we find the budget constraint is binding in all these settings, indicating the available budget would be fully utilized.

Table 18 shows interesting changes in the solutions from different aspects such as network structure, capacity, shortage percentage for different beneficiary types, and proportion of strategic and operational costs. Additionally, Fig. 11 depicts the changes in donation, food availability in each tier as well as in the system, while the budget tightens (from right to left).

With budget reduction, overall capacity decreases and although the total number of foodbanks/FRRAs does not change much, the Tier-I foodbanks operate with minimal storage capacities. At the '0.2x' setting, Fig. 11 shows a significant reduction in storage and workforce capacities (highlighted in red). Table 18 presents the shortage percentage for different beneficiary types. Since capacity is closely associated with donation collection, distribution, and transfer, Fig. 11 further explains the almost linear decrease in food quantity from right to left. Note that although until '0.6x' setting, all available donations are collected, the '0.4x' onwards some donations remain uncollected (at Tier-II), indicating the capacity crunch. A sharp decrease in storage and workforce capacities (more than 70% of base) is observed at '0.2x', whose reflection is also evident in Fig. 11 between '0x' and '0.2x'. Finally, with the tightening of budget, the strategic and operational cost proportions also change. Corroborating with our above observations for the '0.2x' case, we observe that although a minimal investment in capacity is made to sustain the system, budgets are reduced for food purchase and its distribution.

Key observation 6: *Although in non-profit settings, expenditure towards tangible services to beneficiaries is preferred over capacity building, for a system with inadequate infrastructure and running on a tight budget, the beneficiaries cannot be served without capacity building.*

5.8. Adding strategic-to-operational cost proportionality constraint

We conduct this analysis to further explore the effect of changing strategic vs operational cost proportions, by adding a *cost proportionality constraint* to the base model to ensure: "**strategic cost** $\leq \mu\times$ **operational cost**", where μ is a fraction. The budget constraint discussed in Section 5.7 is removed before running this experiment. Through this new constraint, we establish a clear dominance of operational cost over strategic cost. While gradually varying μ and re-solving our model, we present important components from the optimal solution in Table 19. Since in the base case solution of [P], we observe the ratio of strategic to operational cost to be 0.79, for this experiment, we only consider a systematic reduction of μ from that value. In Table 19, note that with $\mu = 0.4$, all capacities (storage, transport, and workforce) reduce drastically and all beneficiaries experience huge shortages. In the line of our discussion in Section 5.7 leading to key observation 5, this experiment again underlines the danger of exercising frugality in infrastructure building, which is essential to ensure the serving of the beneficiaries.

5.9. Equity consideration with different granularities

When demand overwhelms donation quantity and system's capacity, even the increased procurement at Tier-I becomes inadequate to shortages as the storage capacity bottleneck hits. In such resource-constrained situations, it is critical for the foodbank system (and any

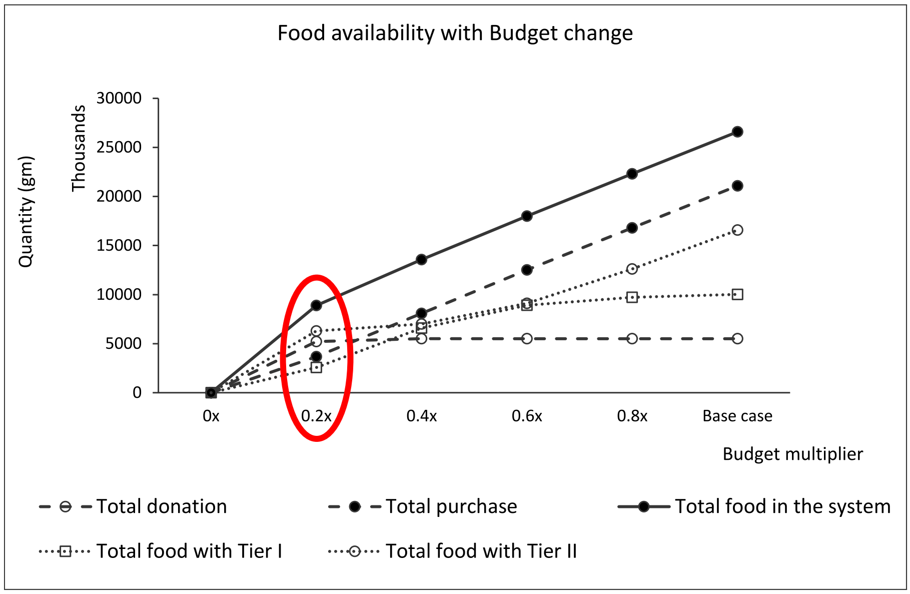


Fig. 11. Effects of budget change on food availability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 19
Effects of adding a Strategic-to-operational cost constraint.

Network	μ := No of foodbanks/FRRAs	0.3 6	0.4 6	0.5 8	0.6 8	0.7 8	Base case (0.79) 8
Capacity	Storage (kg)	5000	5000	35,000	27,000	25,000	25,000
	Transportation (kg)	5400	5400	7400	7400	7400	7600
	Workforce (#)	42	57	367	295	274	271
Shortage (%)	Tier-II Child	61.45	67.18	0	0	0	0
	Tier-II Adult	99.98	100.00	0	0	0	0
	Tier-I Child	90.58	62.86	0	0	0	0
	Tier-I Adult	98.65	100.00	0	0	0	0

non-profit organization) to maintain equity or fairness in distribution. Among different ways of incorporating *equity* in an optimization model, we adopt the *egalitarian* approach of adding a *minimax* term in the objective function of our model [P]. Specifically, we remove the last term from the objective function expression (1) that represents the penalty for beneficiaries' shortages, and call it Z_1. Then we add to Z_1, the appropriate minimax term (see second column of Table 20) with a multiplier M (to make the minimax term's magnitude comparable with Z_1). As the addition of the minimax term makes the objective function nonlinear, we linearize it by the standard technique of replacing the minimax expression with an auxiliary variable $\widetilde{\lambda}$ with appropriate indices and moving the latter in constraint. Table 20 presents five *minimax* variants and their linearization schemes. Since our base case solution for model [P] does not incur shortage for any beneficiary (see Section 4.2), we build a comprehensive case of system-wide shortage by making demand to be twice the base case value (i.e., '2x' setting of Experiment 1). Table 21 presents the detailed shortage analysis for five equity variants, and in the last column, adds the solution without equity consideration (i.e., solution of [P] with '2x' demand). Observe that although total shortage is not too different across the six columns, their distribution among tiers and beneficiary types change interestingly. Below, we explain equity variants representing different granularities and their effects on the shortage distribution.

Through experiments E1 to E5, we exhibit gradual progress in the equity representations. E1 represents the most basic approach among the five variants of equity by considering shortages at both tiers' beneficiary nodes and beneficiary types equally. This is reflected in Table 21 entries, where we see very close shortage values for child and adult (5778 and 5402), and all positive entries under 'Tier and type jointly'. Note that the shortages are distributed much better compared to corresponding entries under the 'No Equity' column. The variant E2 ensures *in-tier equity*, i.e., the model attempts to treat shortage proportions (i.e., shortage to demand ratio) of child and adult beneficiaries at par. We observe some extreme albeit opposite shortage allocations under the E2 and 'No Equity' columns. Particularly, E2 ends up allocating all shortages to Tier-II beneficiaries, ignoring their higher nutritional needs. Therefore, this solution is unacceptable for our case study problem instance. *'In-type' equity* is presented by E3, where shortage proportions of children or adults from different tiers are treated at par. Although we observe a higher shortage in Tier-II (9334) compared to Tier-I (1856), and also a higher shortage for children (7221) compared to adults (3969), the values are less extreme than the 'No Equity' column entries. In the last two variants, while E4 represents an *in-tier-in-type* joint equity without relative penalties to shortages at specific tiers and beneficiary types, E5 includes that information vis $\nu_{\pi m}$ parameter. The higher relative weights of Tier-II child and adult beneficiaries, in conjunction with the *in-tier-in-type equity* constraint, force most shortages to Tier-I (lower priority) in E4 and all shortages in E5.

This experiment shows that the effects of equity considerations on the solution are not straightforward, and the decision-maker should analyze the pros and cons of different equity variants before adopting one.

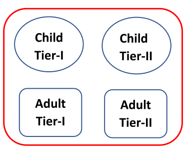
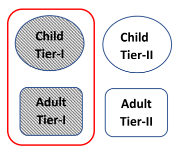
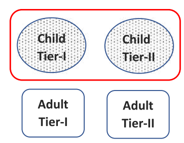
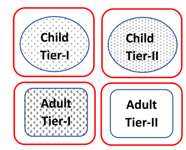
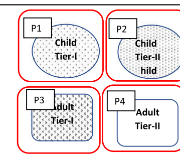
6. Concluding remarks and future work

We present an approach of integrating two tiers having distinctly different levels of donors and foodbanks serving beneficiaries with quite different nutritional requirements. We develop a MIP model that determines – given the sets of potential foodbanks (in Tier-I;

Table 20
Five equity variants — corresponding objective function and constraints.

#	Objective function (minimax)	Linearized objective	Constraints added
E1.	$\text{Min } Z_1 + M \times \max_{\pi\in\Pi, j\in J}\left\{\lambda_{\pi j}\right\}$	$\text{Min } Z_1 + M \times \tilde{\lambda}$	$\tilde{\lambda} \geq \lambda_{\pi j} \quad j \in J, \pi \in \Pi.$
E2.	$\text{Min } Z_1 + M \times \sum_{m\in\mathcal{M}} \max_{j\in J_m}\left\{\frac{\sum_{\pi\in\Pi}\lambda_{\pi j}}{\sum_{\pi'\in\Pi}\sum_{j'\in J_m} D_{\pi' j'}}\right\}$	$\text{Min } Z_1 + M \times \sum_{m\in\mathcal{M}} \tilde{\lambda}_m$	$\tilde{\lambda}_m \geq \frac{\sum_{\pi\in\Pi}\lambda_{\pi j}}{\sum_{\pi'\in\Pi}\sum_{j'\in J_m} D_{\pi' j'}} \quad \forall m \in \mathcal{M}, j \in J_m;$ $\tilde{\lambda}_m \geq 0 \quad \forall m \in \mathcal{M}.$
E3.	$\text{Min } Z_1 + M \times \sum_{\pi\in\Pi} \max_{j\in J}\left\{\frac{\lambda_{\pi j}}{\sum_{j'\in J} D_{\pi j'}}\right\}$	$\text{Min } Z_1 + M \times \sum_{\pi\in\Pi} \tilde{\lambda}_\pi$	$\tilde{\lambda}_\pi \geq \frac{\lambda_{\pi j}}{\sum_{j'\in J} D_{\pi j'}} \quad \forall j \in J, \pi \in \Pi;$ $\tilde{\lambda}_\pi \geq 0 \quad \forall \pi \in \Pi.$
E4.	$\text{Min } Z_1 + M \times \sum_{m\in\mathcal{M}}\sum_{\pi\in\Pi} \max_{j\in J_m}\left\{\frac{\lambda_{\pi j}}{D_{\pi j}}\right\}$	$\text{Min } Z_1 + M \times \sum_{m\in\mathcal{M}}\sum_{\pi\in\Pi} \tilde{\lambda}_{m\pi}$	$\tilde{\lambda}_{m\pi} \geq \frac{\lambda_{\pi j}}{D_{\pi j}} \quad \forall m \in \mathcal{M}, j \in J_m, \pi \in \Pi;$ $\tilde{\lambda}_{m\pi} \geq 0 \quad \forall m \in \mathcal{M}, \pi \in \Pi.$
E5.	$\text{Min } Z_1 + M \times \sum_{m\in\mathcal{M}}\sum_{\pi\in\Pi} v_{\pi m} \max_{j\in J_m}\left\{\frac{\lambda_{\pi j}}{D_{\pi j}}\right\}$	$\text{Min } Z_1 + M \times \sum_{m\in\mathcal{M}}\sum_{\pi\in\Pi} v_{\pi m}\tilde{\lambda}_{m\pi}$	$\tilde{\lambda}_{m\pi} \geq \frac{\lambda_{\pi j}}{D_{\pi j}} \quad \forall m \in \mathcal{M}, j \in J_m, \pi \in \Pi;$ $\tilde{\lambda}_{m\pi} \geq 0 \quad \forall m \in \mathcal{M}, \pi \in \Pi.$

Table 21
Analysis of shortages for five equity variants.

Equities	E1	E2	E3	E4	E5	–
						No equity
Shortage (#)	11,180	11,099	11,190	11,043	11,270	11,251
% shortage	30.41	30.19	30.44	30.04	30.65	30.60
Beneficiary type						
Child	5778	2767	7221	166	11,270	10,058
Adult	5402	8332	3969	10,877	0	1193
Tier-wise						
Tier-I	1536	0	1856	166	11,270	11,245
Tier-II	9644	11,099	9334	10,877	0	6
Tier and type jointly						
Tier-II Child ($v_{\pi m}$ = 1.00)	4626	2767	5625	0	0	1
Tier-II Adult ($v_{\pi m}$ = 0.95)	384	0	260	0	0	1188
Tier-I Child ($v_{\pi m}$ = 0.90)	1152	0	1596	166	11,270	10,057
Tier-I Adult ($v_{\pi m}$ = 0.85)	5018	8332	3709	10,877	0	5

with storage capacity) and 'food recovery and redistribution agencies' [FRRA] (in Tier-II; without storage capacity) – which entities from each tier should be chosen, transport, and workforce capacities, to form an integrated network, connected with donor and beneficiary nodes of the same tier. Our model estimates the optimal cost of building such an ecosystem by minimizing the sum of several fixed, capacity-building, procurement, donation collection, and distribution-related costs. In our case study with a mix of real and realistically estimated parameters, the model produces a base solution (see Section 4.2), illustrates the benefit of integration (see Section 5.6), and presents several insights by conducting a detailed analysis of the effects of changing demand (see Section 5.1), donation quantities (see Section 5.2), and both of those simultaneously (see Section 5.3). Furthermore, we examine the effects of adding a budget constraint (see Section 5.7), a strategic-to-operational cost constraint (see Section 5.8), and equities of different granularities in the egalitarian approach (see Section 5.9).

Insights from our numerical analyses would help the centralized system's decision-maker in recognizing the right courses of action when demand increases (Key observation 1); when it is better to leave some donation uncollected (Key observation 2); when to take initiatives for encouraging cooked food donation from the Tier-II donors (Key observation 3); how the initial capacities (storage, transport, and workforce) influence the overall system cost for designing and running the foodbank logistics network (Key observation 4); how appropriate penalty values help in discouraging wastes and shortages in the system (Key observation 5); and when investing in capacity building (strategic cost) becomes important than direct spending for the beneficiaries to serve them better (Key observation 6).

We end our discussion by indicating some future research directions. First, while we address donation (supply) and demand fluctuations in numerical analysis, embedding different sources of uncertainties in the optimization model itself by adopting stochastic programming or a robust optimization framework is a possibility. Second, the impact of an overall budget constraint and equity consideration together can be interesting. While this work adopts the egalitarian approach of expressing equity at different granularities, some alternate equity representations can be examined. Third, in a multi-objective setting, equity, cost efficiency, and effectiveness (i.e., the 3E's in nonprofit operations management) can be modeled as three objective functions. While our work, being a strategic model, considers donation collection and food packet distribution costs to be proportional to the distances between node pairs, the associated routing decisions may also be integrated, albeit with additional computational complexities. Finally, in addition to receiving donations as food items, the inclusion of financial donations can be considered along with its overheads.

CRediT authorship contribution statement

Ajinkya Tanksale: Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Jyotirmoy Dalal:** Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Nistha Dubey:** Software, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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