Chapter 5: Optimal Design of an Integrated Food Bank Network Considering Nutritional Requirements: Modeling and Case Study

5.1.Introduction

Zero hunger is second sustainable development goal (SDG's) set by United Nations to be achieved by 2030 (United Nations, 2015). It corresponds to end of hunger, achievement of food security, improving nutrition, and the promotion of sustainable agriculture. According to the recent report for assessing the performance of each SDG, food insecurity and hunger is on rise globally (United Nations, 2020) due to pandemic. According to the recent joint report, around 828 million people were affected globally by hunger in 2021(Rigillo et al., 2022). Around 29.3% of global population were severely or moderately food insecure in 2021 and according to projections in 2030, 8% of the world's population will still be hungry (FAO et al., 2022). The figures are relatively more alarming for India. According to the latest Global Hunger Report, India ranks 111th out of 125 countries with state of hunger as "serious" in the country (*Global Hunger Index*, 2023). According to the recent National Family Health Survey, 36% of children under 5 years are stunted, 19% are wasted and 32% are under weight (National Family Health Survey India, 2022). There are several interventions taken by government of India to fight against hunger such as public distribution system, national food security act, mid-day meals. Public Distribution system of India is one of the largest of its kind (Tanksale & Jha, 2015). In spite of all these potential government interventions, hunger, malnutrition, and food insecurity exists in India. The non-government bodies working in India to alleviate hunger are food banks.

Food banks are the entities which collects surplus/leftover food and distributes it to the people in need. The typical supply chain of food banks is characterized by donors (Corporates, industries, farmers, hotels/restaurants, catering agencies, individual), beneficiaries (charitable agencies, old age homes, orphanage, homeless, slum dwellers), food (cooked food, packaged food), food banks (front-end, back-end), and manpower (volunteers, employees). Front-end food banks correspond to the food recovery and redistribution units who distributes food immediately after recovery. Front-end food banks mostly collect cooked food and usually they do not have proper storage facility to store the donated food. On the contrary, back-end food banks have adequate storage facilities (including refrigerated) and they work on both types of food (cooked/packaged). The operations of most food banks are governed using food and monetary donations. These monetary donations are barely enough to sustain their daily operations. Due to this, most food banks depend heavily on their volunteers for their daily operations of collection and distribution. Availability of volunteers are subject to uncertainty. Sometimes due to their unavailability, food collection and distribution could not be performed and that available surplus/leftover food that would have been a source of sustenance to needy people now goes into waste (in case of perishable food). A FAO report estimates that 30% of the food that is produced for human consumption ends up in the waste stream which costs for $1 trillion of economical cost. Food banks which align with two major SDG's - 'Zero Hunger' (SDG 2) and 'Responsible Consumption and Production' (SDG 12), can be considered as a green solution to hunger. Food banks have the required potential to reduce food insecurity and food waste thus improving sustainability.

Several countries are effectively planning food bank supply chain network to reduce food wastage, food insecurity, to fulfil nutritious meal and redistribute the leftover/surplus food.

They have well organized infrastructure and coordination among different food banks which is a strategic outcome to deal with food insecurity and food waste management. However, emergence of Indian food banks and its current network framework is not an outcome of any strategic decision, it started for practicing philanthropy and later emerged as a solution of increased hunger and instant surplus food. Our study presented in Chapter 3 highlights that Indian food banks lacks coordination and therefore available resources could not be shared among them to increase the effectiveness for their collective performance. Food banks operate with limited resources and their operation significantly depends on the availability of volunteers and donations. Effective supply chain network design (SCND) has indispensable role to support food bank operations.

This chapter addresses the strategic problems related to Food banks in India. The contributions of this paper are multi-fold. Firstly, this paper addresses the three important objectives – efficiency, effectiveness, and equity related to food banks in several ways. The efficient food bank system deals with minimization of transportation cost, effective system leads to minimization of undistributed food and equity deals with fulfilment of demand of a particular area in proportion with the total demand (Hasnain et al., 2021). This paper proposes a total of 11 MILP models for supply chain network design of food banks utilizing different sets of objectives and constraints. The purpose of exploring various SCND models related to efficiency, effectiveness, and equity is to assess the performance of these models. Additionally, we proposed a case problem for visualizing and understanding the results of all 11 MILP models. These models will be evaluated on various performance metric such as – shortage, manpower needed, budget needed, budget utilized, number of beneficiaries served. A base model is selected to carry out extensive sensitive analysis and its details is given in subsequent paragraphs. This will also assist researchers and practitioners to opt for the most suitable and well-performed model for relevant studies.

Second important contribution includes the aspect of nutrition in the proposed model. Though nutritious meal is inevitable part of ensuring food security and reducing malnutrition, yet research related to nutrition and SCND are extant. To the best of our knowledge, integration of SCND model for food banks and aspect of nutrition has not been investigated and we try to fill this research gap with the proposed study. Food banks receive variety of food from diverse donors and it becomes consequential to convert these food donations into meal packets which contain optimal nutrition and ensure recommended daily intake of nutrients. The nutritional requirement varies with gender and age group. In the proposed study, we categorized the beneficiaries according to the age group and gender to comply with the data regarding recommended daily intake of nutrients which is mostly age-wise and gender-wise.

The third contribution corresponds to the case study developed on Indian food banks. Framework of Indian food banks differs characteristically due to their different medium and extent of operations and we endeavored this two-tiered network structure of Indian food banks and included our model formulation. We reached out to some major food banks operating in India and collected data using several communication platforms like google meet, emails, and telephonic conversations. The data comprises of location of food banks, location of donors, location of beneficiaries, estimated donation amount, frequency of donation, and estimated demand.

Lastly, we carried out extensive sensitivity analysis on the selected base model out of the proposed 11 MILP models. The selected model inhibits key possible characteristics which a typical food bank must possess. Further, the shortage model is selected and extensive sensitivity analysis has been performed on supply donation, demand, budget, volunteers. Moreover, sensitivity analysis is also performed on total cost minimization model. Summarizing all this, our mathematical model is designed to address the following research objectives:

1. To design a food distribution network that optimally selects food banks, allocates donors to these food banks, and matches food banks with beneficiaries, while considering donor quantities, beneficiary needs, and potential expansions in food bank capacities.
2. To develop methodologies for integrating age profiles and nutritional requirements of beneficiaries from diverse socio-economic backgrounds into strategic decision-making frameworks.
3. To design and evaluate a system that effectively adapts to and manages uncertainties in supply and demand while accounting for budgetary constraints.
4. To quantitatively assess the benefits of integrating two currently independent operational tiers, focusing on the potential for increased synergy and efficiency.

5.2.Model formulation

This section deals with the nascent food bank supply chain in developing countries like India in great depth. This paper proposes a MILP model for solving multi-echelon multi-product network design problem inspired by Indian food banks.

5.2.1. Problem description

The number of Indian food banks are growing at a vast rate, extending their reach to deep remote areas. The fundamental operation of food bank comprises of collection/recovery and distribution of surplus/leftover food to the deprived section of society. However, functionality, characteristics, attributes and entities of food banks varies according to the several intrinsic and regional factors. Indian food banks can be fragmented into two-tiers based on their mode of operation, scale of operation, type of donors/suppliers, type of donations permissible and type of beneficiaries. Table 5.1 differentiates the tiers based on extrinsic and intrinsic characteristics.

Table 5.1: Characteristic of Tier-1 and Tier-2 food banks operating in India

Characteristics	Tier-1 Food Banks	Tier-2 Food Banks
Mode of Operation	Bank-end	Front-end
Scale of operation	Large scale	Small scale (works in remote towns and cities)
Types of donors	Corporates, big farmers, Food industry, Supermarkets	Individual practice, Hotels, Restaurants, Temples, Catering agencies
Type of beneficiaries	Old age homes, orphanage, School going students	Slum residents, homeless, poor people
Types of donations permissible	Food grains, pulses, fruits and vegetables, packaged food such as biscuits	Ready-to-eat food (Cooked), fruits and vegetables.
Operational characteristics		
Transportation mode	Big and mini trucks	Cars, motor-bikes possessed by volunteers
Storage	Available	Not available
Manpower	Hired personnel and volunteers	Volunteers

The above features demonstrate that food banks are operational in a hierarchical fashion India. For instance, *India Food Banking Network* is one of the prime tier-1 food banks operating in

India with a network of more than 30 regional food banks and 150 non-governments beneficiary organizations working under its umbrella (*India FoodBanking Network*, n.d.). Similarly, there are other tier-1 food banks such as *Robin Hood Army*, *Feeding India* operating in India. The tier-2 food banks such as *Indian Roti Bank*, *Anna Patra,* sometimes work in silos and have strong regional presence in their respective operating areas. The tier-1 food banks usually have association with big corporate houses, food industries, supermarket chains from where they procure a large amount of food donations through big and mini trucks. These donations are stored in warehouse and later assigned staff break-bulk the donations into packets and distributes the packets to the beneficiaries. Moreover, some tier-2 food banks (working in the same region) receive food donations from the tier-1 food banks. Apart from this, tier-2 food banks collect donations from hotels, restaurants, catering agencies and individuals. These donations are typically of ready-to-eat in nature and therefore in dire need to distribute immediately after recovery (front-end model). The daily operation of recovery and redistribution of leftover food of tier-2 food banks is carried out by vehicles possessed by volunteers which is usually motor-bikes and cars.

The target beneficiaries of tier-1 food banks usually receive some minimum food support from various government initiatives, like mid-day meal (school going children receives lunch in school), public distribution system (people receive grains, pulses, oil etc. on a minimum fixed price). Symptoms of malnutrition can be found in these beneficiaries. Therefore, tier-1 food banks act as a supplementary program to contribute to government initiatives by providing nutritious food to the targeted beneficiaries. The beneficiaries of tier-2 food banks belong to marginalized section of society where the above-mentioned government initiatives fail to reach. The people residing in slum, homeless, daily wagers are more prone to food insecurity.

Hunger is prevalent in this class of beneficiaries and thus there is dire need of food support. Therefore, we have assigned beneficiaries of tier-2 food banks as priority-1 beneficiaries, which seeks food to get away hunger. Similarly, beneficiaries of tier-1 food banks are called as priority-2 beneficiaries, which seeks food to supplement their nutritional requirement. The target beneficiaries of tier-1 and tier-2 food banks are different. However, types of beneficiaries remain same. We have categorized beneficiaries in to five types – children (1 to 9-year-old), boys (10- to 18-year-old), girls (10- to 18-year-old), men, and women as described in Figure 5.1.

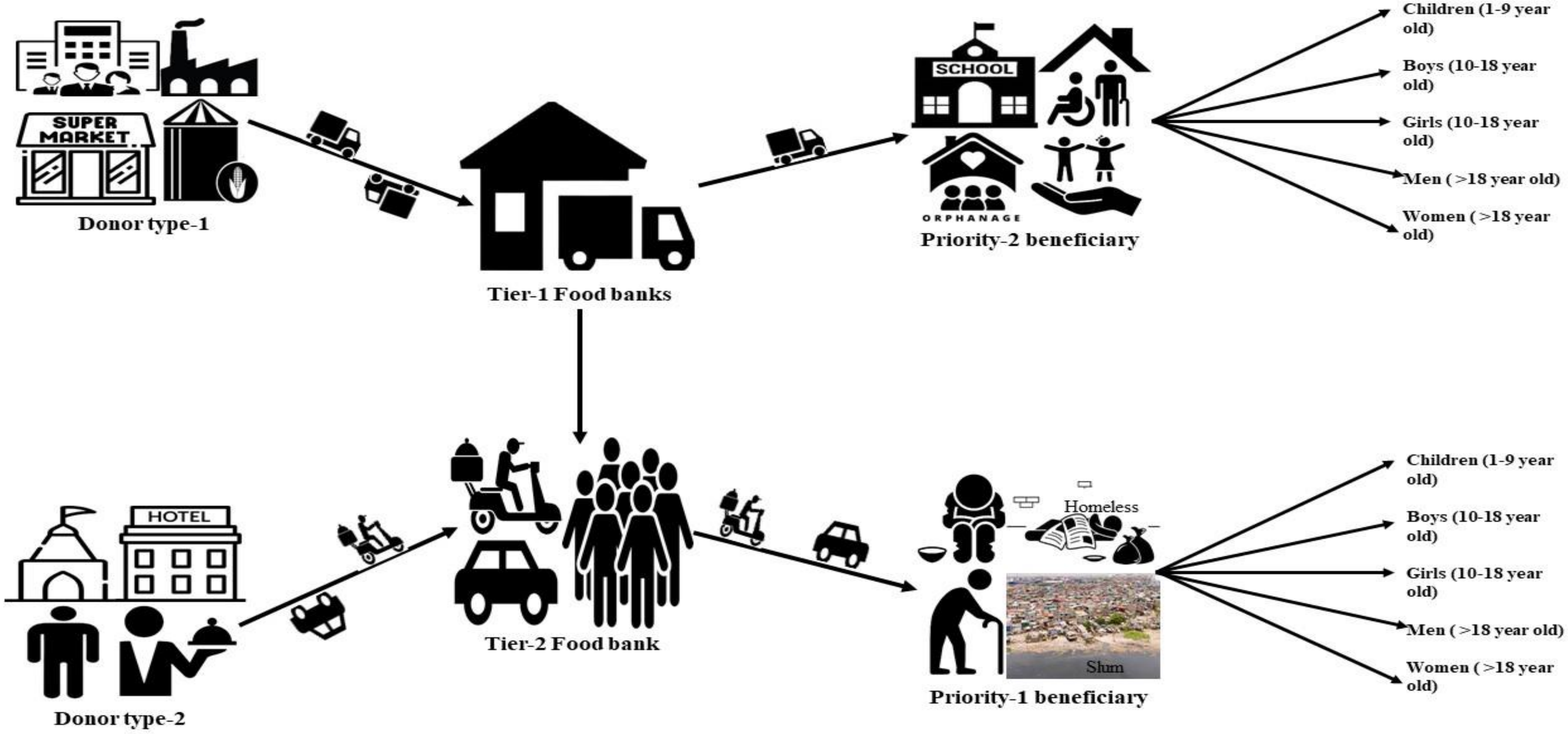


Figure 5.1: Schematic diagram of food bank network operating in India

Some salient features and assumptions of the proposed model is described below-

- Donor sets for tier-1 and tier-2 food banks is mutually exhaustive.
- Tier-1 food banks have storage (along with refrigeration units), transportation and manpower capacities. Combination of hired personnel and volunteers are assumed to be present at existing tier-1 food banks.
- It is assumed that storage facility is not available in tier-2 food banks. Also, tier-2 food banks completely rely on volunteer chain to sustain the daily operation of collection and distribution.
- Beneficiary sets for both tiers of food banks is mutually exhaustive. Beneficiary set for tier-2 food banks is called as priority-1 beneficiaries and priority-2 beneficiaries for tier-1 food banks.
- Each beneficiary location can have six types of beneficiaries – infants, children, boys, girls, men, and women.
- The food packet made at all food banks is associated with types of beneficiaries i.e. a total of six types of food packets can be made operating food bank.

5.2.2. Notation

5.2.2.1. Sets and indices

$\boldsymbol{F}$	Set of all food items	$F = \{1, 2, \dots, f\}$
$\boldsymbol{I_1}$	Set of donors who deliver food to Tier-1 food banks	$I_1 = \{1, 2, \dots, i_1\}$
$\boldsymbol{I_2}$	Set of donors who deliver food to Tier-2 food banks	$I_2 = \{i_1 + 1, i_2 + 2, \dots, i_2\}$
I	set of all donors (indexed by i)	$I = \{1, 2, \dots, i\}$
$\boldsymbol{J_1}$	Set of priority-2 beneficiary nodes (Only served by Tier-1 food banks)	$J_1 = \{1, 2, \dots, j_1\}$

$\boldsymbol{J_2}$	Set of priority-1 beneficiary nodes (Only served by Tier-2 food banks)	$J_2 = \{j_1 + 1, j_2 + 2, \dots, j_2\}$
$\boldsymbol{J}$	Set of locations of all beneficiaries	$J = \{1, 2, \dots, j\}$
$\boldsymbol{B_1}$	Set of existing Tier-1 food banks	$B_1 = \{1, 2, \dots, b_1\}$
$\boldsymbol{B_2}$	Set of existing Tier-2 food banks	$B_2 = \{b_1 + 1, b_1 + 2, \dots, b_2\}$
$\boldsymbol{\gamma}$	Set of existing food banks $B_1 \cup B_2$	$\gamma = \{1, 2, \dots, b_2\}$
$\boldsymbol{\bar{B}_1}$	Set of new Tier-1 food banks	$\bar{B}_1 = \{b_2 + 1, b_2 + 2, \dots, b_3\}$
$\boldsymbol{\bar{B}_2}$	Set of new Tier-2 food banks	$\bar{B}_2 = \{b_3 + 1, b_3 + 2, \dots, b\}$
$\boldsymbol{\bar{\gamma}}$	Set of potential locations for new food banks ($\bar{B}_1 \cup \bar{B}_2$)	$\bar{\gamma} = \{b_2 + 1, b_2 + 2, \dots, b_4\}$
$\boldsymbol{\hat{A}}$	Set of all Tier-1 food banks ($B_1 \cup \bar{B}_1$)	
$\boldsymbol{\hat{B}}$	Set of all Tier-2 food banks ($B_2 \cup \bar{B}_2$)	
$\boldsymbol{B}$	Set of all food banks ($\hat{A} \cup \hat{B}$)	$B = \{1, 2, \dots, b\}$
$\boldsymbol{S}$	Storage capacity alternatives (Only available at Tier-1 food banks)	$S = \{1, 2, \dots, s\}$
$\boldsymbol{K_1}$	Transport capacity alternatives for Tier-1 food banks	$K_1 = \{1, 2, \dots, k_1\}$
$\boldsymbol{K_2}$	Transport capacity alternatives for Tier-2 food banks	$K_2 = \{1, 2, \dots, k_2\}$
$\boldsymbol{\Pi}$	Set of beneficiary types based on age group (indexed by π)	
$\boldsymbol{N}$	Set of nutrients (indexed by n)	$N = \{1, 2, \dots, n\}$

5.2.2.2. Parameters

L_s	Storage capacity with alternative, $s \in S$ (in kg)
T_k	Transport capacity with alternative, $k \in K_1 \cup K_2$ (in kg)

θ_b	Initial storage capacity at existing Tier-1 food banks, $b \in B_1$ (in kg), $\theta_b = 0, if\ b \in \bar{B}_1$
ρ_b^1	Initial transport capacity at existing Tier-1 food banks, $b \in B_1$ (in kg), $\rho_b^1 = 0\ if\ b \in \bar{B}_1$
ρ_b^2	Initial transport capacity at existing Tier-2 food banks, $b \in B_2$ (in kg), $\rho_b^2 = 0\ if\ b \in \bar{B}_2$
σ_b^1	Number of volunteers at existing Tier-1 food banks, $b \in B_1$, $\sigma_b^1 = 0\ if\ b \in \bar{B}_1$
σ_b^2	Number of volunteers at existing Tier-2 food banks, $b \in B_2$, $\sigma_b^2 = 0\ (if\ b \in \bar{B}_2)$
ψ	Meal equivalent handled by one staff/volunteers (in kg)
$\eta_{\pi j}$	The demand at beneficiary location *j* for beneficiary type $\pi \in \Pi$ (in kg)
ϕ_{fn}	Amount of nutrient $n \in N$ in food $f \in F$ (in gram/kg)
$\delta_{\pi n}$	Recommended daily intake for nutrient *n* for beneficiary type $\pi \in \Pi$ (in gram)
$£_\pi$	Maximum permissible weight for packet category $\pi \in \Pi$ (in kg)
$\bar{£}_\pi$	Minimum permissible weight for packet category $\pi \in \Pi$(in kg)
Q_{fi}	Quantity of food $f \in F$ available for donation at donor $i \in I$ (in kg)
P_1	The total budget available for strategic decisions
P_2	The total budget available for operational decisions
C_b	Cost of opening a new food bank
$\bar{C}_b$	Cost of closing an existing food bank
C_{sb}	Cost of installing/expanding storage capacity of size *s* at tier-1 food bank
C_{kb}^1	Cost of installing/expanding transport capacity of size $k \in K$ at tier-1 food bank
C_{kb}^2	Cost of installing/expanding transport capacity of size $k \in \bar{K}$ at tier-2 food bank
C_m	Cost of hiring unit manpower
α_f	Cost of purchasing unit of food, $f \in F$
β_π	priority/relative weightage of beneficiary categories
d_{ij}	Distance between node pair (i, j) (in kms)

5.2.3. Decision variables

$$x_b = \begin{cases} 1, \text{if existing food bank, b} \in \gamma \text{ is closed} \\ 0, \text{otherwise} \end{cases}$$

$$x_b^2 = \begin{cases} 1, \text{if existing tierII food bank, b} \in \text{B}_2 \text{is closed} \\ 0, \text{otherwise} \end{cases}$$

$y_b = \begin{cases} 1, \text{if food bank is opened at potential location } b \in \bar{\gamma} \\ 0, \text{otherwise} \end{cases}$

$y_b^2 = \begin{cases} 1, \text{if tier} - 2 \text{ food bank is opened at potential location } b \in \bar{B}_2 \\ 0, \text{otherwise} \end{cases}$

$u_b = \begin{cases} 1, \text{if food bank } b \in B \text{ is operating} \\ 0, \text{otherwise} \end{cases}$

$w_{sb} = \begin{cases} 1, \text{If storage capacity of size, } s \in S \text{ is installed at tier} - 1 \text{ food bank } b \in \hat{A} \\ 0, \text{otherwise} \end{cases}$

$w_{kb}^1 = \begin{cases} 1, \text{If transportation capacity } k \in K_1 \text{ is installed at tier} - 1 \text{ food bank } b \in \hat{A} \\ 0, \text{otherwise} \end{cases}$

$w_{kb}^2 = \begin{cases} 1, \text{If transportation capacity } k \in K_2 \text{ is installed at tier} - 2 \text{ food bank } b \in \hat{B} \\ 0, \text{otherwise} \end{cases}$

r_b = Number of personnel hired at food banks

$\omega_{f\pi b}$ = The total quantity of food $f \in F$ for beneficiary type $\pi \in \Pi$ at food banks

$\tau_{\pi b}$ = Number of packets for beneficiary type $\pi \in \Pi$ made at food banks

$\hat{q}_{fb}$ = Quantity of food $f \in F$ available for distribution at food banks

q_{fb} = Quantity of food $f \in F$ purchased at food banks

q_{fib}^1 = Quantity of food $f \in F$ collected from donor type 1 $i \in I_1$ by tier-1 food bank $b \in \hat{A}$

q_{fib}^2 = Quantity of food f collected from donor type 2 $i \in I_2$ by tier-2 food bank $b \in \hat{A}$

$o_{\pi bj}$ = Number of meal packets for beneficiary type $\pi \in \Pi$ moved from food bank $b \in B$ to beneficiary $j \in J$

q_{fab} = Quantity of food f shipped from tier-1 food bank $a \in \hat{A}$ to tier-2 food bank $b \in \hat{B}$

$z_{\pi j}$ = Demand shortage of beneficiary type $\tau \in \partial$ at beneficiary location $j \in J$

λ = Maximum shortage

5.2.4. Formulation

Model ***P***

Minimize:

$$Z = \sum_{\pi \in \Pi} \sum_{j \in J} z_{\pi j}$$ (Base Model Objective)

Subject to;

$$u_b = 1 - x_b \quad \forall b \in \gamma \quad (2)$$

$$u_b = y_b \quad \forall b \in \bar{\gamma} \quad (3)$$

$$\sum_{s \in S} w_{sb} \leq u_b \quad \forall b \in \hat{A} \quad (4)$$

$$\sum_{k \in K_1} w_{kb}^1 \leq u_b \quad \forall b \in \hat{A} \quad (5)$$

$$\sum_{k \in K_2} w_{kb}^2 \leq u_b \quad \forall b \in \hat{B} \quad (6)$$

$$r_b \leq M * u_b \quad \forall b \in B \quad (7)$$

$$q_{fb} \leq M * u_b \quad \forall b \in B, \forall f \in F \quad (8)$$

$$\sum_{b \in \bar{\gamma}} C_b * u_b + \sum_{s \in S} \sum_{b \in \hat{A}} C_{sb} * L_s * w_{sb} + \sum_{k \in K} \sum_{b \in \hat{A}} C_{kb}^1 * T_k * w_{kb}^1 + \sum_{k \in \bar{K}} \sum_{b \in \hat{B}} C_{kb}^2 * T_k * w_{kb}^2 + \sum_{b \in B} C_m * r_b + \sum_{b \in \gamma} \bar{C}_b * u_b \leq P_1 \quad (9)$$

$$\sum_{i \in I_1} \sum_{j \in \hat{A}} \sum_{f \in F} d_{ij} * q_{fij}^1 + \sum_{i \in \hat{A}} \sum_{j \in \hat{B}} \sum_{f \in F} d_{ij} * q_{fij} + \sum_{i \in \hat{A}} \sum_{j \in J_1} \sum_{\pi \in \Pi} d_{ij} * o_{\pi bj} + \sum_{i \in I_2} \sum_{j \in \hat{B}} \sum_{f \in F} d_{ij} * q_{fij}^2 + \sum_{i \in \hat{B}} \sum_{j \in J_2} \sum_{\pi \in \Pi} d_{ij} * o_{\pi bj} + \sum_{f \in F} \sum_{b \in B} q_{fb} * \alpha_f \leq P_2 \quad (10)$$

$$\sum_{b\in\hat{A}} q_{fib}^{1} \leq Q_{fi} \quad \forall i \in I_1, f \in F \tag{11}$$

$$\sum_{b\in\hat{B}} q_{fib}^{2} \leq Q_{fi} \quad \forall i \in I_2, f \in F \tag{12}$$

$$\sum_{f\in F}\sum_{i\in I_1} q_{fib}^{1} \leq \rho_b^1 * u_b + \sum_{k\in K_1} T_k * w_{kb}^{1} \quad \forall b \in \hat{A} \tag{13}$$

$$\sum_{f\in F}\sum_{i\in I_2} q_{fib}^{2} \leq \rho_b^2 * u_b + \sum_{k\in K_2} T_k * w_{kb}^{2} \quad \forall b \in \hat{B} \tag{14}$$

$$\sum_{f\in F} \hat{q}_{fb} + \sum_{f\in F, a\in\hat{B}} q_{fba} \leq \rho_b^1 * u_b + \sum_{k\in K_1} T_k * w_{kb}^{1} \quad \forall b \in \hat{A} \tag{15}$$

$$\sum_{f\in F} \hat{q}_{fb} \leq \rho_b^2 * u_b + \sum_{k\in K_2} T_k * w_{kb}^{2} \quad \forall b \in \hat{B} \tag{16}$$

$$\sum_{f\in F}\sum_{i\in I_1} q_{fib}^{1} + \sum_{f\in F} q_{fb} \leq \theta_b * u_b + \sum_{s\in S} L_s * w_{sb} \quad \forall b \in \hat{A} \tag{17}$$

$$\sum_{f\in F}\sum_{i\in I_1} q_{fib}^{1} + \sum_{f\in F} q_{fb} \leq \sigma_b^1 * u_b + r_b * \psi \quad \forall b \in \hat{A} \tag{18}$$

$$\sum_{f\in F}\sum_{i\in I_2} q_{fib}^{2} + \sum_{f\in F} q_{fb} + \sum_{f\in F}\sum_{a\in\hat{A}} q_{fab} \leq \sigma_b^2 * u_b + r_b * \psi \quad \forall b \in \hat{B} \tag{19}$$

$$\sum_{i\in I_1} q_{fib}^{1} + q_{fb} = \hat{q}_{fb} + \sum_{a\in\hat{B}} q_{fba} \quad \forall b \in \hat{A}, \forall f \in F \tag{20}$$

$$\sum_{i\in I_2} q_{fib}^{2} + q_{fb} + \sum_{a\in\hat{A}} q_{fab} = \hat{q}_{fb} \quad \forall b \in \hat{B}, \forall f \in F \tag{21}$$

$$\sum_{\pi\in\Pi} \omega_{f\pi b} = \hat{q}_{fb} \quad \forall b \in B, \forall f \in F \tag{22}$$

$$\phi_{fn} * \omega_{f\pi b} \geq \tau_{\pi b} * \delta_{\pi n} \quad \forall f \in F, \forall \pi \in \Pi, \forall b \in B, \forall n \in N \tag{23}$$

$$\sum_{j\in J_1} o_{\pi bj} \leq \tau_{\pi b} \quad \forall b \in \hat{A}, \forall \pi \in \Pi \tag{24}$$

$$\sum_{j\in J_2} o_{\pi bj} \leq \tau_{\pi b} \quad \forall b \in \hat{B}, \forall \pi \in \Pi \tag{25}$$

$\sum_{b \in \hat{A}} o_{\pi b j} + z_{\pi j} = \eta_{\pi j}$	$\forall j \in J_1, \forall \pi \in \Pi$	(26)
$\sum_{b \in \hat{B}} o_{\pi b j} + z_{\pi j} = \eta_{\pi j}$	$\forall j \in J_2, \forall \pi \in \Pi$	(27)
$\sum_{f \in F} \omega_{f \pi b} \leq £_{\pi} * \tau_{\pi b}$	$\forall b \in \hat{B}, \forall \pi \in \Pi$	(28)
$\sum_{f \in F} \omega_{f \pi b} \geq \bar{£}_{\pi} * \tau_{\pi b}$	$\forall b \in \hat{B}, \forall \pi \in \Pi$	(29)

The objective function Z (Base Model Objective) minimizes the total shortage. Constraints (2)- (3) ensure opening and closing decisions. Constraints (4) – (8) ensure that capacity (storage, transportation, manpower) instalment/expansion and procurement of food will only be done for operating or functional food banks. Constraint (9) ensures the total cost incurred in opening of food banks, closing of food banks, capacity instalment and expansion and manpower hiring should be less than the available strategic budget. Similarly, constraint (10) limits the cost incurred in the operational decision. Constraints (11) - (12) ensure that the total amount of food that is available for collection from the donors is within the limit of the committed donations. Constraints (13) – (14) ensure capacity acquisition related to transportation on collection side. Similarly, constraints (15) – (16) ensure the same is applicable on distribution side. Constraint (17) employs storage capacity restriction on the amount of total food that could be collected or purchased. Constraints (18) – (19) depict the total manpower needed to carry out the collection and distribution process. Constraints (20) – (21) are the flow conservation constraints. Constraint (22) restricts the total food available in all packet types should be equal to the total food available for distribution to the beneficiaries. Constraints (23) imposes minimal nutritional requirement that must be available in the made packets. Additionally, this constraint also converts the total amount of food available for distribution into number of meal packets. Constraints (24) – (25) ensure that total number of packets of each packet type moved from food banks to beneficiaries should not exceed the number of packets of respective type available at food banks. Constraints (26) – (27) are demand constraints. Constraints (28) – (29) impose restriction on maximum and minimum permissible weights of the packets of respective packet type.

5.2.5. Variations in the model

There could be several variations to the proposed model in terms of its objective function. Generally, minimization of cost function is employed to assess the performance of the models pertaining to supply chain design. However, this paper addresses the supply chain network design of food banks which is humanitarian in nature. The prime objective of food banks could be to maximize the effectiveness (by maximizing the total shipment of food to beneficiaries, therefore minimizing shortages) which is represented by base model P. The other variations of the base model P is presented by proposing different objectives and set of constraints on top of base model. The objective of base model is referred as Base model Objective (Z). Similarly, alternate models to the base model are developed by considering alternate objectives Objective-I (Z_1) in P_1, Objective-II (Z_2) in P_2, Objective-III (Z_3) in P_3, Objective-IV (Z_4) in P_4, Objective-V (Z_5) in P_5, Objective-VI (Z_6) in P_6, Objective-VII (Z_7) in P_7, Objective-VIII (Z_8) in P_8, Objective-IX (Z_9) in P_9, and Objective-X (Z_{10}) in P_{10}.

The model P does not ensure fair distribution of food to the beneficiaries. So, the other objective function could be to ensure effectiveness as well as equitable distribution. The quantity of food shipped to the beneficiaries should be in the ratio of their demands to ensure equitability. This can be done by changing the objective function of model P. The updated model is represented by model P_1.

Model $\boldsymbol{P_1}$	
Minimise $Z_1 = \sum_{\pi\in\Pi}\sum_{j\in J}\frac{z_{\pi j}}{\eta_{\pi j}}$	(I)
Subject to;	
constraints (2) – (29)	

The constraints for model P_1 is constraints (2) – (29). The above two models ensure effectiveness and equitability but fails to ensure fairness in the distribution. Equity is one of the criteria for fairness in distribution as reported by Sengul Orgut et al. (2018). The model for supply chain network design of food banks incorporating equity feature is denoted by model P_2. Model P_2 can be obtained from the base model by adding a pair of constraints and Objective-II (Z_2).

Model $\boldsymbol{P_2}$		
Minimise: $Z_2 = \sum_{\pi\in\Pi}\sum_{j\in J} z_{\pi j}$		(II)
Subject to;		
constraints (2) – (29)		
$-\varepsilon \leq \frac{z_{\pi j}}{\sum_{\pi\in\Pi}\sum_{j\in J} z_{\pi j}} - \frac{\eta_{\pi j}}{\sum_{\pi\in\Pi}\sum_{j\in J}\eta_{\pi j}} \leq \varepsilon$	$\forall j \in J, \forall\pi \in \Pi$	(30)

For ensuring perfect equity in shortages ($\epsilon = 0$), Constraint (30) enforces fraction of total shortage at a beneficiary is exactly equal to the fraction of total demand of that beneficiary. However, deviations from perfect equity is observed in real time operations. For example, if two conditions arise such that decision maker have to opt from whether to ensure equity and do not distribute more food to the locations with high demands or violate equity and distribute excess food to the locations with high demands, decision maker usually chooses latter. In those cases, Constraint (30) ensures that absolute difference between the fraction of total shortage of a beneficiary and fraction of total demand should not exceed ϵ.

We have incorporated different beneficiary types (Π) based on age-group (children, boys, girls, men and women). Sometimes, children are more prone to malnutrition and need immediate nutritious food assistance for their sustenance. In order to prioritize certain beneficiary, different weights (β_π) has been assigned. The model with weights assigned to beneficiary types is represented by P_3.

Model $\boldsymbol{P_3}$	
Minimise: $Z_3 = \sum_{\pi\in\Pi}\sum_{j\in J}\beta_\pi * z_{\pi j}$	(III)
Subject to;	
constraints (2) – (29)	

The Objective-III (Z_3) minimizes the weighted shortage value. P_3 encourages least shortage values for the beneficiaries having higher weights. In all the above variations, we have incorporated two parameters for budget i.e., strategic budget and operational budget. Strategic budget incurred when a food bank is opened or closed, storage capacity is installed or expanded, acquisition of transport capacities or its expansion and in manpower hiring. Operational budget is needed for travelling cost incurred during collection and distribution drives, and additional food purchase cost to meet the demand of beneficiaries. In order to capture the intricacies of keeping a common budget model P_4 was developed which enabled us to get some insights on separate budget values. The Objective-IV(Z_2) in model P_4 minimizes the total shortage in the system considering a single parameter for common budget.

Model $\boldsymbol{P_4}$	
Minimise: $Z_4 = \sum_{\pi\in\Pi}\sum_{j\in J} z_{\pi j}$	(IV)
Subject to;	

$$\sum_{b\in\overline{\gamma}} C_b * u_b + \sum_{s\in S}\sum_{b\in\hat{A}} C_{sb} * L_s * w_{sb}$$
$$+ \sum_{k\in K}\sum_{b\in\hat{A}} C_{kb}^1 * T_k * w_{kb}^1$$
$$+ \sum_{k\in\overline{K}}\sum_{b\in\hat{B}} C_{kb}^2 * T_k * w_{kb}^2 + \sum_{b\in B} C_m * r_b$$
$$+ \sum_{b\in\gamma} \bar{C}_b$$
$$* u_b \sum_{i\in I_1}\sum_{j\in\hat{A}}\sum_{f\in F} d_{ij} * q_{fij}^1 \qquad \forall j \in J, \forall \pi \in \Pi \quad (31)$$
$$+ \sum_{i\in\hat{A}}\sum_{j\in\hat{B}}\sum_{f\in F} d_{ij} * q_{fij} + \sum_{i\in\hat{A}}\sum_{j\in J_1}\sum_{\pi\in\Pi} d_{ij} * o_{\pi bj}$$
$$+ \sum_{i\in I_2}\sum_{j\in\hat{B}}\sum_{f\in F} d_{ij} * q_{fij}^2 + \sum_{i\in\hat{B}}\sum_{j\in J_2}\sum_{\pi\in\Pi} d_{ij} * o_{\pi bj}$$
$$+ \sum_{f\in F}\sum_{b\in B} q_{fb} * \alpha_f \le P$$

constraints (2) – (8) and constraints (11)- (29) of model P

The above variations in the model ($P_1$to P_4) tries to minimize the total shortage in the demand of beneficiaries in the existing system. Food banks generally operates in resource scare environment. One of the primal objectives of food banks is to minimize their total expenditure since they have limited access to monetary funds to carry out strategic decisions. Objective-V in the model P_5 minimizes the total cost incurred for designing supply chain network for food banks. The objective function (35) minimizes the total cost incurred in the network for opening and closing of food banks, instalment/expansion of storage capacities to tier-1 food banks, instalment/expansion of transport capacities at food banks, hiring manpower for the food banks, procurement cost and transportation cost. Moreover, to ensure some shortage value, the shortage decision variable has been penalized in the objective function (35).

Model $\boldsymbol{P_5}$

Minimise: (V)

$$\sum_{b\in\overline{\gamma}} C_b * u_b + \sum_{s\in S}\sum_{b\in\hat{A}} C_{sb} * L_s * w_{sb} + \sum_{k\in K}\sum_{b\in\hat{A}} C^1_{kb} * T_k * w^1_{kb} + \sum_{k\in\overline{K}}\sum_{b\in\hat{B}} C^2_{kb} * T_k * w^2_{kb} + \sum_{b\in B} C_m * r_b + \sum_{b\in\gamma} \bar{C}_b * u_b + \sum_{i\in I_1}\sum_{j\in\hat{A}}\sum_{f\in F} d_{ij} * q^1_{fij} + \sum_{i\in\hat{A}}\sum_{j\in\hat{B}}\sum_{f\in F} d_{ij} * q_{fij} + \sum_{i\in\hat{A}}\sum_{j\in J_1}\sum_{\pi\in\Pi} d_{ij} * o_{\pi bj} + \sum_{i\in I_2}\sum_{j\in\hat{B}}\sum_{f\in F} d_{ij} * q^2_{fij} + \sum_{i\in\hat{B}}\sum_{j\in J_2}\sum_{\pi\in\Pi} d_{ij} * o_{\pi bj} + \sum_{f\in F}\sum_{b\in B} q_{fb} * \alpha_f + penalty * \sum_{j\in J}\sum_{\pi\in\Pi} z_{\pi j}$$

Subject to;

constraints (2) – (8) and constraints (11)- (29) of model P

Another approach for minimizing the shortage could be to follow the min-max approach. For this study one of the objective functions could be to minimize the maximum shortage value. Constraints (37) ensures a maximum value for shortage variable among all nodes and beneficiary types and later objective function (36) minimizes this shortage. This model could prove to be useful in worst demand/shortage distribution.

Model $\boldsymbol{P_6}$

Minimise: λ (VI)

Subject to;

constraints (2) – (29)

$$\lambda \geq z_{\pi j} \qquad \forall j \in J, \forall \pi \in \Pi \quad (37)$$

Model P_6 minimizes the maximum shortage value. In order to accommodate equitability in the maximum shortage to demand ratio model P_7 has been proposed. Constraint (38) ensures a maximum shortage to demand ratio for λ and later objective function (36) minimizes this ratio, thus, model P_7 minimizes the maximum equitable shortage λ.

Model $\boldsymbol{P_7}$

Minimise: λ (VII)

Subject to;

constraints (2) – (29)

$$\lambda \geq \frac{z_{\pi j}}{\eta_{\pi j}} \quad \forall j \in J, \forall \pi \in \Pi \quad (38)$$

Model P_8 poses min-max shortage constraints on the beneficiary types. Essentially, it ensures equitable distribution of food across all the beneficiary types available at all beneficiary nodes. Constraints (39) is utilized for minimizing the maximum intrinsic shortage (across all beneficiary types available on the beneficiary nodes).

Model $\boldsymbol{P_8}$

Minimise: λ (VIII)

Subject to;

constraints (2) – (29)

$$\lambda \geq \sum_{\pi \in \Pi} z_{\pi j} \quad \forall j \in J \quad (39)$$

Similarly, model P_9 poses min-max shortage constraints on the beneficiary locations. It ensures total food delivered at each location in the network is equitable. Constraints (40) is utilized for minimizing the maximum extrinsic shortage (within all beneficiary nodes for single beneficiary type).

Model $\boldsymbol{P_9}$

Minimise: λ (IX)

Subject to;

constraints (2) – (29)

$$\lambda \geq \sum_{j \in J} z_{\pi j} \quad \forall \pi \in \Pi \quad (40)$$

Model P_{10} imposes min-max weighted shortage within all beneficiary nodes for each beneficiary types.

Model $\boldsymbol{P_{10}}$		
Minimise: λ		(X)
Subject to;		
constraints (2) – (29)		
$\lambda \geq \sum_{j \in J} \beta_{\pi} * z_{\pi j}$	$\forall \pi \in \Pi$	(41)

5.3. Case Study

In this section, we design a case study for supply chain network design on the food banks operating in national capital of India (Delhi). We have used this city because the hierarchy of all the types food banks operating here captures the overall properties of food bank operating in any region in India. In this city, a total of 15 food banks are operating in silos (five tier-1 food banks and 10 tier-2). We anonymize the names of food banks in this case study for avoiding the impact of result on these food banks. Tier-1 food banks are named as fb1_1, fb1_2, fb1_3 and so on till fb1_5 and tier-2 food banks are named as fb2_1, fb2_2, fb2_3 and so on till fb2_10. We reached out to the executives of all the food banks operating in the selected area through virtual platforms such as e-mails, google meet, telephonic interviews and social media. Two tier-1 (named as fb1_1 and fb1_2) and two tier-2 (named as fb2_1 and fb2_2) food banks agreed for detailed interviews and to provide us with the required dataset. Out of all 5 tier-1 food banks we considered two (fb1_1 and fb1_2) as existing and remaining 3 as potential locations for opening new tier-1 food banks (fb1_3, fb1_4, and fb1_5). Similarly, out of 10 tier-2 food banks we took two as existing tier-2 food bank (fb2_1 and fb2_2) and remaining 8 as potential locations for new tier-2 food banks (fb2_3, fb2_4, and so on till fb2_10) as given in Figure 5.2.

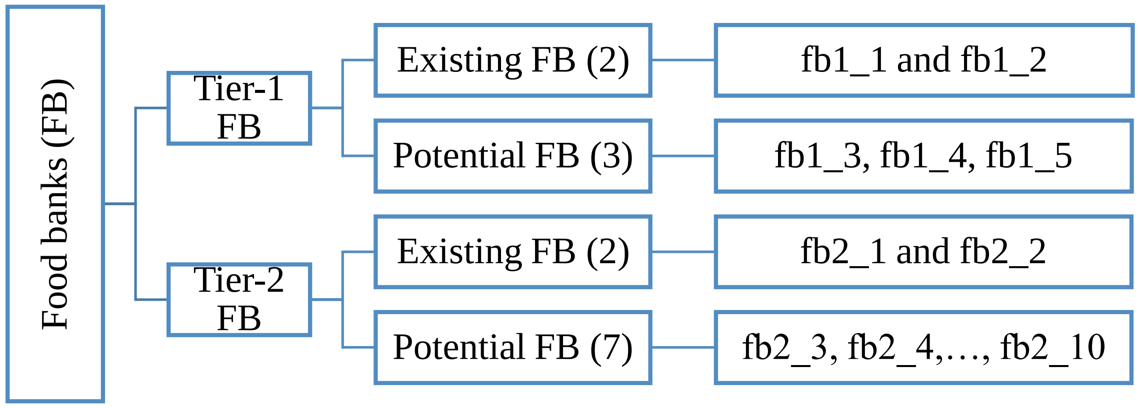


Figure 5.2: Nomenclature of tier-1 and tier-2 food banks

The number of priority-1 and priority-2 beneficiary locations used in this study are 60 and 16, respectively. The total demand for priority-1 and priority-2 beneficiaries are 6971 and 11411 units, respectively. Tier-1 food banks are allowed fulfill only the demand of priority-2 beneficiaries and tier-2 food banks while tier-2 food banks are allowed to fulfill the demand of only priority-1 beneficiaries. The actual location of food banks (existing and potential), location of beneficiaries (priority-1 and priority-2), is plotted using Google maps and is given in Figure 5.3. Each food banks have been queried with the fields given under "Data queried" columns in Table 5.2.

Table 5.2: Dataset related to existing food bank network

Entities in the model	Data queried
Donors	Number of donors and their location
	Types of donors
	Typical food available for donation
	Quantity of each type of food donated
	Frequency of donation
	Name of food bank it is affiliated to
Food banks	Name of food bank and its location
	Existing capacities (storage & transport)

	Number of employees and active volunteers Class of beneficiaries to be served Number of beneficiaries of each type
Beneficiaries	Class of beneficiaries Types of beneficiaries

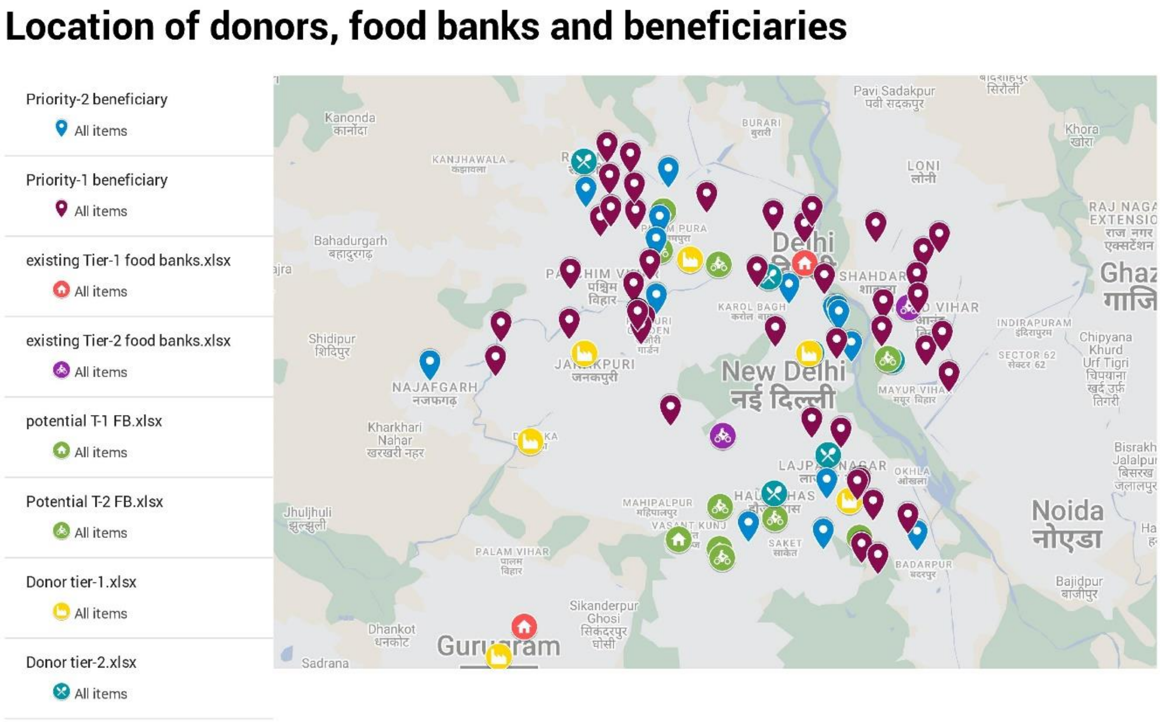


Figure 5.3: Location of donors, beneficiaries and food banks

Each existing tier-1 and tier-2 food banks have some existing capacities. The storage (θ_b), transport (ρ_b^1), and manpower (σ_b^1) capacity of existing tier-1 food banks are 1000kgs, 1000kgs, and 200 units, respectively. Since tier-2 food banks mostly work as food recovery and redistribution units therefore in this study the storage capacities of existing food banks are taken as 0. The transport (ρ_b^2) and manpower (σ_b^2) capacities of existing tier-2 food banks are 1000kgs and 200 units, respectively. We have taken three levels of alternatives for capacities - small, medium, and high. The capacity alternatives for storage, S is taken as 2000, 4000, and 8000 kgs. The transport capacity alternative for tier-1 food banks (K_1) are taken as 1500, 3000, and 6000 kgs. Similarly, the transport capacity alternatives for tier-2 food banks (K_2) are taken as 1000, 2000, and 4000 kgs. In addition to manpower capacity, it can be noted that each volunteer can handle a certain amount of food and therefore, we have considered weight of food that can be handled by a volunteer (ψ) as 5 kgs. The number of donors associated with tier-1 of food banks ($|I_1|$) are found to be 6 and donates a total of 11 types of food. Similarly, number of donors associated with tier-2 food banks ($|I_2|$) are 6 and donates five types of cooked food. A total of 17 types of food ($|F|$=17) has been considered in this study which is most commonly donated by donors and distributed by the food banks. Each food is characterized with its associated nutrient contents. Primarily, we have considered five types of nutrients ($|N|$=5, indexed by n) in our study – Carbohydrates, proteins, fats, vitamins and minerals. The amount of each nutrient in the considered foods (ϕ_{fn}) are obtained from USDA National Nutrient Database for Standard Reference (U.S. Department of Agriculture, 2021). The data for recommended daily intake of nutrients for Indians according to age group ($\delta_{\pi n}$) have been acquired from the report of Indian Council of Medical Research (ICMR, 2020). The detailed data for supply donation and demand is briefly explained in the subsequent paragraphs.

Since food banks in India is fledgling and therefore due to limited availability of skilled manpower for carrying out record keeping, the records available with them for some of the data fields of Table 5.2 is further need to be processed/ simulated. For instance, for the donor entities getting exact data for the amount of food for each type available at the donor locations (supply) is quite assiduous task especially for donors of Tier-2 food banks since they entirely rely on their volunteer for carrying out all the operations. We received an estimated data for supply and demand for each donor and beneficiary location, respectively from both tiers of food banks. The estimated data received for supply donation from each donor (Q_{fi}) is considered into the account without any modifications. The total donation available for tier-1 and tier-2 food banks is 3501 kgs and 1999 kgs, respectively. However, we need to transform the total estimated demand of each beneficiary location (j) into beneficiary-type (π) wise demand ($\eta_{\pi j}$). In this paper, we have considered five types of beneficiaries (based on their age group) on each demand/beneficiary location as given in Figure 5.1. For translating the total demand at each location into demand of each beneficiary type at that location, we have used the age profiling ratio (Census of India, 2011). Age profile depicts the percentage of population lies in any particular age group. The total estimated demand at each beneficiary location is multiplied with the age profiling ratio of specific beneficiary type to get the demand of that particular beneficiary type at each location ($\eta_{\pi j}$).

The proposed model involves two types of decision – strategic and operational. The strategic decision is opening and closing of food banks, capacity acquisition and expansion decision, manpower hiring decision and the operational decisions are food procurement decision and travelling decisions. The budget kept for strategic decision is 1.5 crore and for operational decision is 10 lakhs. These values are estimated based on interviews. Each decision is associated with a cost. Cost of opening and closing a food bank is taken as 10,000 units. We have scaled down the cost value according to the total budget. Cost of installing/expanding storage capacity is taken as 100 per unit storage. Similarly, cost of installing transport capacity at tier-1 and tier-2 food banks is taken as 500 units per kg and 250 units per kg, respectively. Fuel cost for transporting food between nodes in the network is taken as 0.05 units per unit distance per unit load. Cost of hiring unit manpower is taken as 10,000 units. Food procurement cost requires cost of unit kg of all seventeen foods considered in the study. In the case design actual cost of foods as well as real distances between locations are considered. Distance between two locations is computed using BING maps API.

It is worth noting that the proposed model helps to transform the donations (in kgs) to number of meal packets having desired level of nutrients for each beneficiary type. The total supply donation received from tier-1 and tier-2 donors is 3500 kgs and 2000 kgs, respectively. The total demand for the all the beneficiaries in the network is 18382 units (total demand for priority-2 beneficiaries is 6971 units and total demand for priority-1 beneficiaries is 11411 units).

All the 11 models are evaluated on the case study data and peculiar characteristics of the each of these models is reported in the subsequent sections. Based on the generated results a base model is selected and extensive sensitivity analysis is employed on the base model to understand its behavior by changing the value of parameters slightly.

5.4.Computational Experiments

In this section we provide the results on the case problem. The whole computational experiment section is divided into two sections. Firstly, we present the results of all 11 models and point out some unique properties of all the models on some indicators. In the second section, extensive sensitivity analysis is carried out on a base model and results are presented. The objective of the computational experiments is multi-fold. Firstly, it explicates all the models according to some common indicators. Secondly, it describes the unique and common characteristics of all the models. Thirdly, a base model is chosen for extensive sensitivity analysis. This helps to understand the change in pattern of the base model results by fluctuating the different parameters value.

Param Shivay supercomputer facility has been used to conduct all the experiments. Each computing node has 192 GB of RAM, and there are 212 of them. The supercomputer Param Shivay contains two Intel Xeon SKL G-6148 processors with a combined memory bandwidth of 25 GB/sec and a processing frequency of 2.4 GHz. Experiments were carried out using the state-of-the-art Gurobi solver. The following section depicts the results of all the 11 models.

5.4.1 Results

This section endeavors a thorough analysis of the results obtained for all the 11 models on the case problem. The potential decisions in all the given 11 models are opening and closing decisions, capacity acquisition and expansion decisions, food purchase decision by each food bank, amount of donation to collect from each donor by each food bank, amount of demand of each beneficiary to be fulfilled by each food bank, number of food packets to be made from the food collected and purchased. The opening and closing decision correspond to the number of tier-1 and tier-2 food banks are opened, number of tier-1 and tier-2 food banks closed. The capacity acquisition decision entails storage, transport and manpower decisions. Storage related decisions are expansion of storage capacities at existing tier-1 food banks, installation of storage capacities at newly opened tier-1 food banks. Decisions related to transport capacities are expansion of transport capacities at existing tier-1 and tier-2 food banks, installation of transport capacities at newly opened tier-1 and tier-2 food banks. Manpower decisions comprises of hiring decision on existing and newly opened tier-1 and tier-2 food banks. A summarized result of all the 11 models is given in Table 5.3. In all the 11 models there are some common characteristics which is used to compare the results all these 11 models. Though there are several common characteristics but, in this problem, we'll be focusing only on those which is able to facilitate performance measure. Since the budget is fixed in all the models except one (P5). Therefore, we are considering the aspects which can improve the outcomes of food banks in terms of total number of beneficiaries served, total budget utilized, total collection. For example, for food bank shortage is one of the most crucial factors to consider under the given resource and budget constraint. Similarly, utilization of the given budget to ensure food reaches to the people in need is consequential. Detailed results of each model are discussed in the subsequent paragraphs.

Table 5.3: Summarized results of all the 11 models

	Shortage (P)	Equitable (P1)	Perfect Equity (P2)	Weighted shortage (P3)	Shortage with single Budget (P4)	Total cost minimization (P5)	Min-max shortage (P6)	Min-max equitable shortage (P7)	Min-max intrinsic shortage (P8)	Min-max extrinsic shortage (P9)	Min-max weighted shortage (P10)
Objective	1505	3.32	1704	120400	1617	17672726	5	0	21	323	22050
Operating food bank	5	4	4	4	4	5	4	4	4	4	5
Newly opened	1	0	0	0	0	1	0	0	0	0	1
Closed	0	0	0	0	0	0	0	0	0	0	0
Storage Capacity	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Transport capacity tier-1	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Transport capacity tier-2	5000	5000	6000	5000	5000	7000	6000	6000	6000	5000	5000
Manpower tier-1	407	417	330	417	404	405	380	330	363	417	407
Manpower tier-2	768	768	830	768	753	955	780	830	797	768	768
Opening cost	100000	0	0	0	0	100000	0	0	0	0	100000
Closing cost	0	0	0	0	0	0	0	0	0	0	0
Storage cost	400000	400000	400000	400000	400000	400000	400000	400000	400000	400000	400000
Transport cost for tier-1	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000
Transport cost for tier-2	1250000	1250000	1500000	1250000	1250000	1750000	1500000	1500000	1500000	1250000	1250000
Total Manpower cost	11750000	11850000	11600000	11850000	11570000	13600000	11600000	11600000	11600000	11850000	11750000
Total collection at tier-1 FB	1096	618	782	1589	3419	3501	1561	718	622	1724	1397
Total purchase tier-1 FB	3746	4280	3598	3294	1405	1329	3119	3662	3955	3175	3429

	Shortage (P)	Equitable (P1)	Perfect Equity (P2)	Weighted shortage (P3)	Shortage with single Budget (P4)	Total cost minimization (P5)	Min-max shortage (P6)	Min-max equitable shortage (P7)	Min-max intrinsic shortage (P8)	Min-max extrinsic shortage (P9)	Min-max weighted shortage (P10)
Tier-1 to Tier-2	14	0	0	15	0	4	0	0	4	73	0
Total Food at tier-1 FB for distribution	4828	4897	4380	4869	4824	4826	4680	4380	4574	4826	4826
Total collection at tier-2 FB	497	1057	1146	878	1914	1999	1105	1110	1210	542	1230
Total purchase at tier-2 FB	6489	5943	6234	6108	5003	6125	5975	6270	5968	6385	5769
Total Food at tier-2 FB for distribution	7000	7000	7380	7000	6918	8128	7080	7380	7182	7000	7000
Total Priority2 beneficiaries fulfilled	6971	6971	6325	6971	6968	6971	6755	6325	6634	6971	6971
Total Priority1 beneficiaries fulfilled	9906	9906	10353	9906	9797	11411	9910	10353	10149	9798	9831
Total Shortage	**1505**	**1505**	**1704**	**1505**	**1617**	**0**	**1717**	**1704**	**1599**	**1613**	**1580**
Total Travelling cost	7501	7304	7091	8175	6813	5982	8099	7186	7378	7261	7497
Total Purchase cost	867908	878907	834460	819136	273187	316744	649840	707353	885199	805202	761947
Unused operational budget	124590	113790	158449	172689	-	-	342062	285461	107423	187537	230556
Runtime	7200	7200	7200	7200	7200	2423	7200	7200	7200	7200	7200
MIPGap (%)	0.04	0.06	0.33	0.04	0.06	0.01	0.26	0.17	0.03	0.2	0.16

In the model P, objective is to minimize the shortage in the network. The total shortage in the network is 1504 units, accounting for 87% and 100% fulfillment of demand of priority-1 and priority-2 beneficiaries, respectively. The total number of newly opened food banks in this model is 1 at fb2_13. The total storage capacity is expanded at fb1_1 and fb1_2 (both existing tier-1 food banks) by 4000 kgs, 2000 kgs each. However, in all the models this value is same. Similarly, no food banks are closed in all the 11 models provided above. Transport capacity is expanded at fb1_1 and fb1_2 by 1500 kgs each. Similarly, transport capacity is expanded at fb2_1 by 1000 kgs and fb2_2 by 1500 kgs and 2000 kgs is installed at fb2_13. The number of personal hired at tier-1 and tier-2 food bank is 407 and 768, respectively. Strategic and operational budget utilization for this model is 100% and 88%. The percent of available donation collected by tier-1 and tier-2 food banks are 31% and 25%, respectively. The amount of collected food by both tier-1 and tier-2 food banks is quite low which can lead to food wastage of near-expiry foods. So, in order to ensure all the available food should be collected we imposed equality instead of less than equal to on the supply constraints (Constraint 11 and Constraint 12). The result of this variation is discussed in the sensitivity analysis section. It is worth noting that 14 kgs of staple food (wheat) is moved from tier-1 food bank (fb1_2) to newly opened tier-2 food bank (fb2_13). The total quantity of food purchased by tier-1 and tier-2 food banks are 3746 kgs and 6489 kgs, respectively.

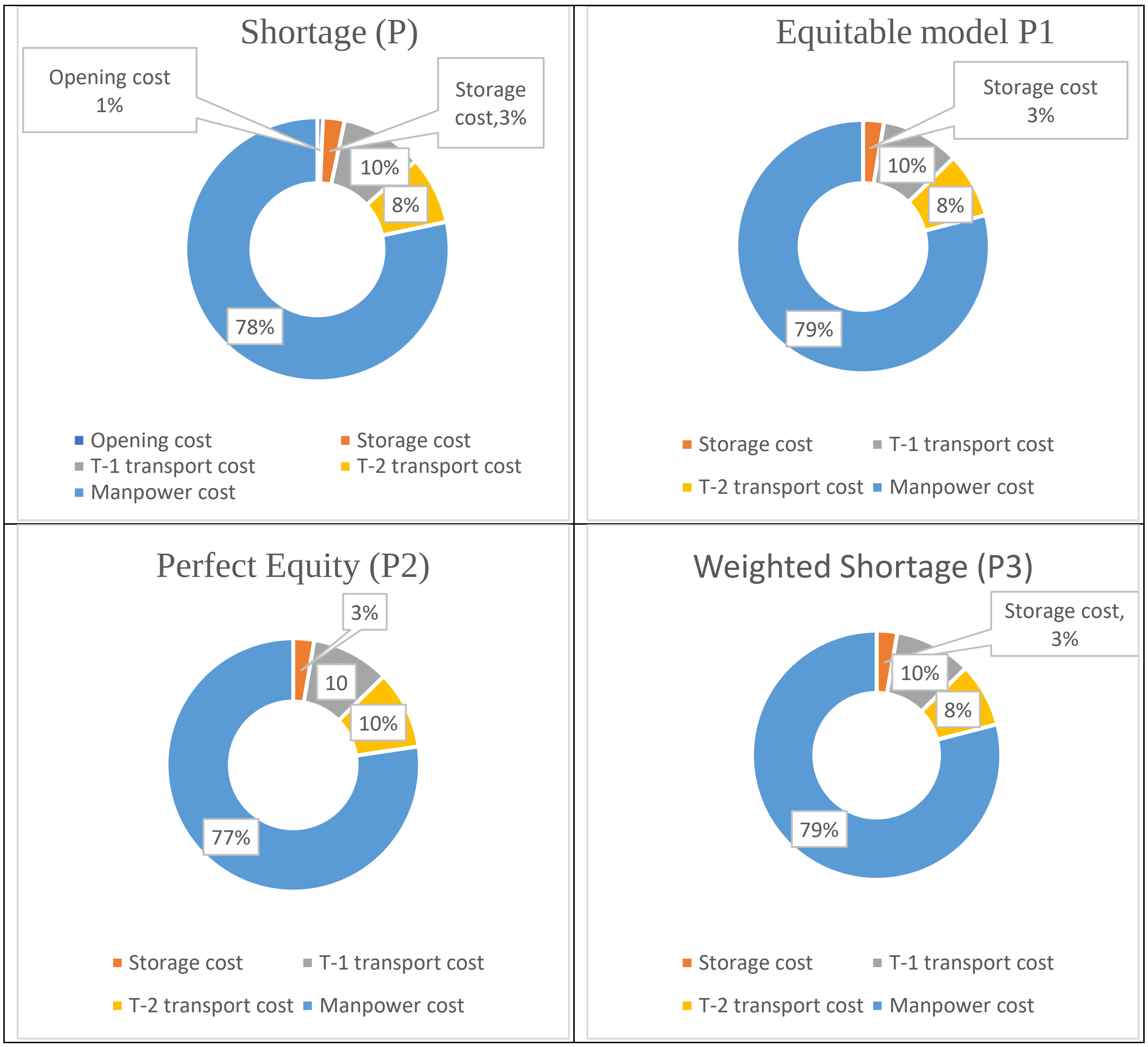
From Table 5.3, it can be noted that for some indicators values remain same across all columns i.e., across all models. For example, total storage capacity expanded and thus its storage cost remains same in all the 11 models. Similar pattern can be seen for number of food banks closed and total transport capacities expanded at existing tier-1 food banks. Hence, transport cost at tier-1 food banks remains same and closing cost is zero across all the models. However, transport capacity distribution for tier-2 food banks differs across all models either in terms of total capacity or in terms which capacity alternative is chosen for existing and newly opened food banks. Similarly, manpower is hired at newly opened and existing tier-1 and tier-2 food banks differently. Table 5.4 shows number of manpower hired at operating food banks. The newly opened food banks in Shortage (P), Total cost minimization (P5) and, min-max weighted shortage (P10) are fb2_13, fb2_15, and fb2_11, respectively.

Table 5.4: Manpower hiring distribution in the operating food banks

Model	**Existing Tier-1 FB**		**Existing Tier-2 FB**		**Newly opened tier-2 FB**
	fb1_1	**fb1_2**	**fb2_1**	**fb2_2**	
Shortage (P0)	188	219	134	**300**	334
Equitable (P1)	201	216	134	**634**	0
Perfect equity (P2)	133	197	209	**621**	0
Weighted shortage (P3)	219	198	**634**	134	0
Shortage with one budget (P4)	188	216	133	**620**	0
Total cost minimization (P5)	**217**	188	192	133	630
Min-max shortage (P6)	166	214	284	**496**	0
Min-max equitable shortage (P7)	198	132	**582**	248	0
Min-max intrinsic shortage (P8)	152	211	300	**497**	0
Min-max extrinsic shortage (P9)	220	197	134	**634**	0
Min-max weighted shortage (P10)	190	217	134	**300**	334

It is worth noting that most manpower is hired at tier-2 food banks. Specifically, in nearly all the models maximum manpower at existing food bank is hired at fb2_2 which is a tier-2 food bank. Moreover, a significant percentage of strategic budget is utilized in hiring manpower.

Strategic budget accounts for cost incurs in opening new food banks, closing existing food banks, installing or expanding storage capacities at newly opened or existing tier-1 food banks, transport capacities installed or expanded at tier-1 and tier-2 food banks, hiring manpower at tier-1 and tier-2 food banks. The expenditure distribution of strategic budget in all the models is given in Figure 5.4.



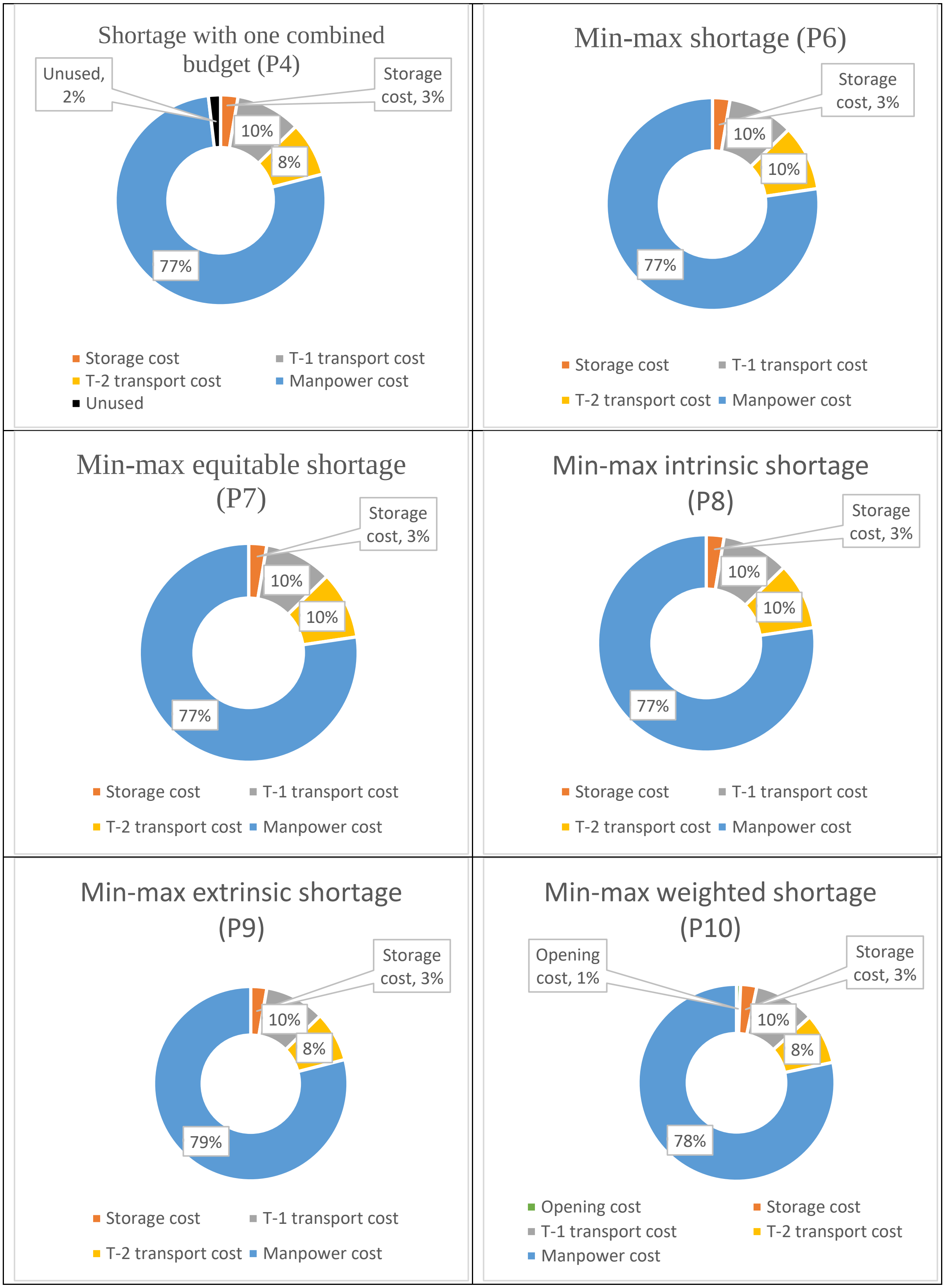


Figure 5.4: Total strategic budget expenditure distribution in all models

The above figure depicts that strategic budget is utilised in all the models except the shortage with one budget model (P5). The unused strategic budget in this model accounts only for 2% of entire strategic budget. As it can be clearly seen that manpower hiring accounts for 77% to 79% of the total strategic budget. Similarly, cost incurred in expansion and installation of transport capacities at operating tier-1 and tier-2 food banks accounts for 8% to 10% in nearly all the models. The minimum total budget needed to attain a zero shortage in the system is given by the model (P5). The peculiar characteristic of this model is that it collects all the donations available at donor and collection is 100% in the model. Similar type of characteristic can be seen for shortage with single budget model (P4). The pattern of percentage of donation undertaken by operating ier-1 and tier-2 food banks are given in Figure 5.5.

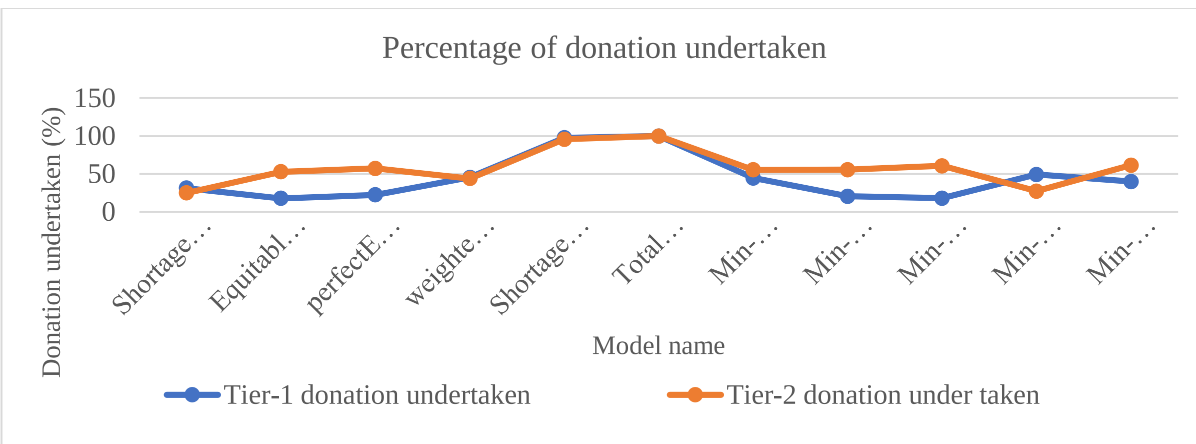


Figure 5.5: Percent available donation undertaken in all models

The operational budget accounts for travelling cost and food purchase cost and its distribution is given in Table 5.3. In order to fulfil the demand of beneficiaries, food banks collect available donation as well as purchases food. The purchase and donation behavior of all the models is given in Figure 5.6.

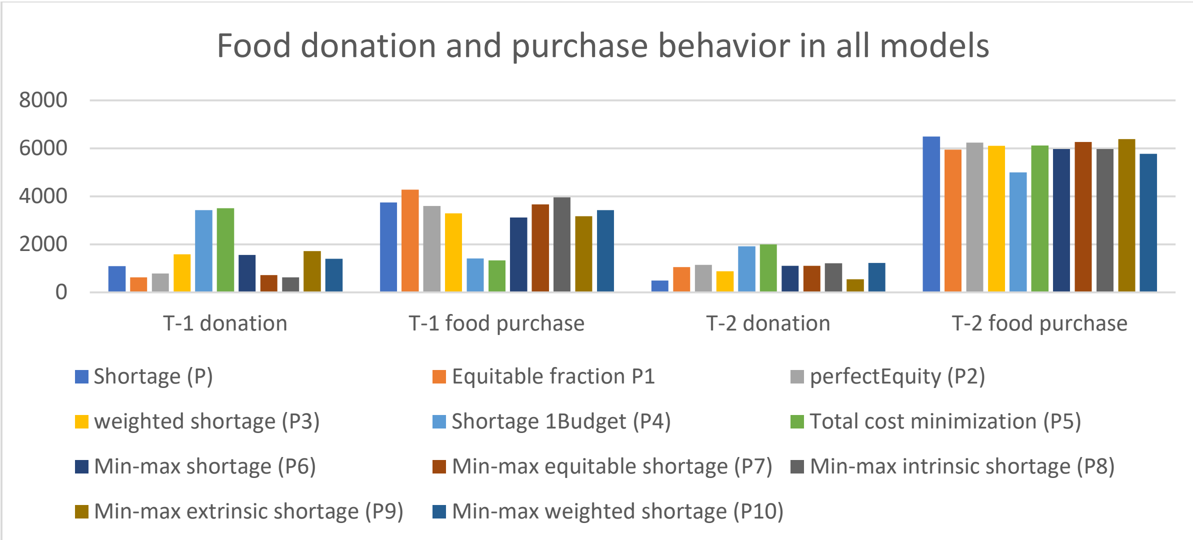


Figure 5.6: Food donation and purchase behavior in all models

As it can be clearly outlined from Figure 5.6, heavy purchase is made at tier-2 food banks in comparison to tier-1 food banks. Also, food traversed from tier-1 to tier-2 food banks is scarce due to high travelling cost incurred in the transportation. Available donation for tier-1 food banks is 3500 kgs and undertaken donation ranges between 17% to 49% for all the models except P4 and P5. Similarly, available donation for tier-2 food banks is 2000 kgs and undertaken donation ranges between 24% to 61% for all the models except P4 and P5. According to the detailed results collected food and purchased food is mostly “Indian bread” and “Banana”, respectively in all the 11 models. The possible reason for this could be the abundant availability of Indian bread and its carbohydrate. The plausible reason for banana as most purchased food could be due to its lower price and higher nutrient contents.

The shortage model (P) captures nearly all the indicators in an optimal way. Also, the primary objective of food banks aligns with that of shortage model (P) and therefore we conducted a comprehensive sensitivity analysis on the shortage model. In order to better understand the comparison and performance of each of the objectives, we have plotted a comparison matrix by solving for one model and recording the values of objective function for all the other models as shown in Table 5.5. In Table 5.5, the bold cells represent the objective values which is used in the corresponding model to as minimization function. The values of objectives of other models are computed and shown in the respective rows.

Table 5.5: Comparison of different objective values recorded for each model

Objectives	BASE	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}
BASE	**1505**	52.68	1505	111110	1505	15875409	483	1	483	841	67280
Z_1	1505	**3.32**	1504	97260	1505	15886211	574	1	1505	574	43200
Z_2	1704	31.79	**1704**	124897	1704	15841551	53.20	0.09	185.35	381	30861
Z_3	1505	53.28	1505	**101500**	1505	15827311	250	1	306	694	55520
Z_4	1617	62.95	1617	97060	**1617**	15000000	146	1	146	1461	87660
Z_5	0	0	0	0	0	**17672726**	0	0	0	0	0
Z_6	1717	92.20	1717	127838	1717	15657939	**5.02**	1	25.08	361	36117
Z_7	1704	31.80	1704	124915	1704	15714539	53.20	**0.09**	185.35	381	30867
Z_8	1599	55.60	1599	108453	1599	15892577	21.03	1	**21.03**	690	55211
Z_9	1613	65.95	1613	119400	1613	15812463	216	1	290	**323**	32300
Z_{10}	1580	22.93	1580	110250	1580	15769444	421	1	1192.75	441	**22050**

As we can see from Table 5.5, model P_7 and model P_2 (row Z_2 and Z_7) is giving the nearly the same values for each of the objectives and therefore, we can eliminate out one with lesser total cost metric which is P_7 in our case.

5.5.Sensitivity Analysis

In this section, we will present a comprehensive sensitivity analysis on all the parameters used in the model formulation. In addition, we present analysis on some of the other models derived from variation of the base model (P). The sensitivity analysis would be instrumental to generate insights for food banks based on several decisions such as expansion, reduction, optimal number of volunteers needed, cost to be incurred while hiring individuals.

5.5.1. Sensitivity analysis on shortage model (P)

Due to the inclusive nature of shortage model, it has been chosen for the comprehensive sensitivity analysis part. Sensitivity analysis is performed on the resources and parameters that are uncertain and limited in nature. Precisely, sensitivity analysis is performed to examine the impact of changes in donations (supply), demand, volunteer, strategic budget, operational budget. Moreover, sensitivity analysis is performed for the equity model (P2) and total cost minimization model (P5). The overall sensitive analysis section is divided into seven section, each section dedicated to (supply), demand, volunteer, strategic budget, operational budget, perfect equity model, and total cost minimization model.

5.5.2. Sensitivity analysis on food donation

Food donations are uncertain in nature and therefore its variation should be analyzed to comment on the robustness of the model. The parameter associated with food donation (supply) for food f at donor location i is Q_{fi}. The effect of change by increasing and decreasing donation. The current donation Q_{fi} is increased by 5% up till it becomes double of the current donation. Similarly, it is decreased by 5% till it becomes zero. So, we have created total 40 instances of the same problem by only changing the donation (supply) parameter (increasing and decreasing the donations) with one additional instance concerning base case. The variation in the values of objective function (shortage) is shown in Figure 5.7. The base case of the model which exhibits the current donation value is depicted by axis point 100 and highlighted by black rhombus in all the subsequent graphs.

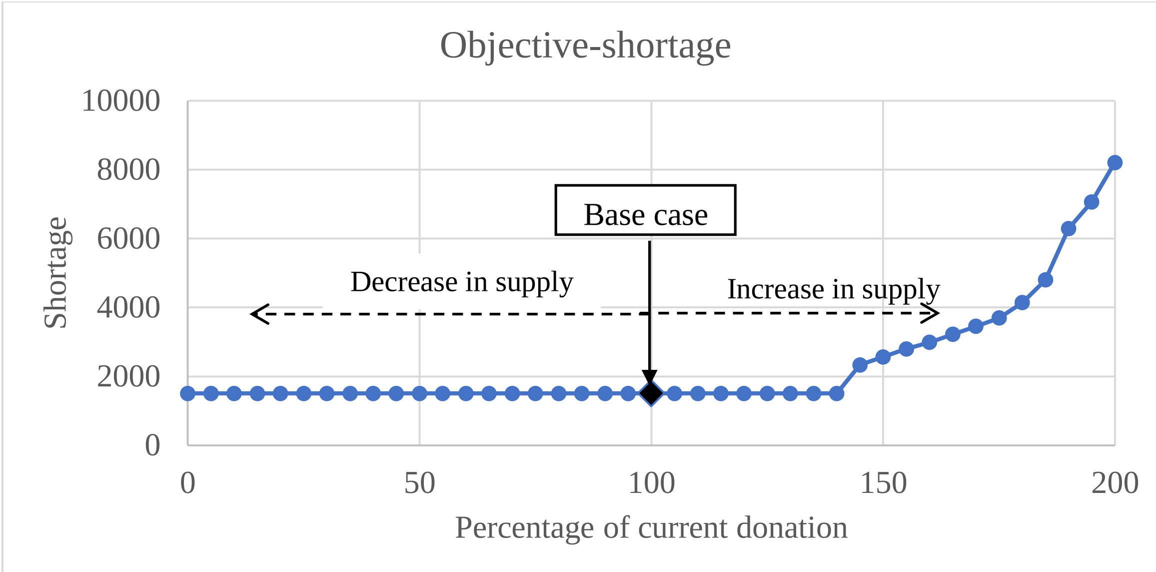


Figure 5.7: Variation in the shortage value with variation in donation

As it can be seen from the Figure 5.7, that even after increasing the supply donation value of shortage increases. Moreover, decreasing the supply values do not impart any effect on shortage value in the network. Specifically, sudden shortage increase occurs when supply donation is increased by 45% and starts increasing monotonically from this point. The is very peculiar behavior observed in this case. Ideally, by increasing supply, shortage should decrease. Now, the total donations are collected since we have imposed equality sign for the supply constraints. In addition to collection of donations, food banks purchases food to meet the beneficiary's requirement. So, in order to understand this increasing pattern in shortage, we need to understand the pattern of food purchase decision and unused operational budget. The food purchase (in kgs) and unused operational budget have been plotted for all the 41 instances in Figure 5.8.

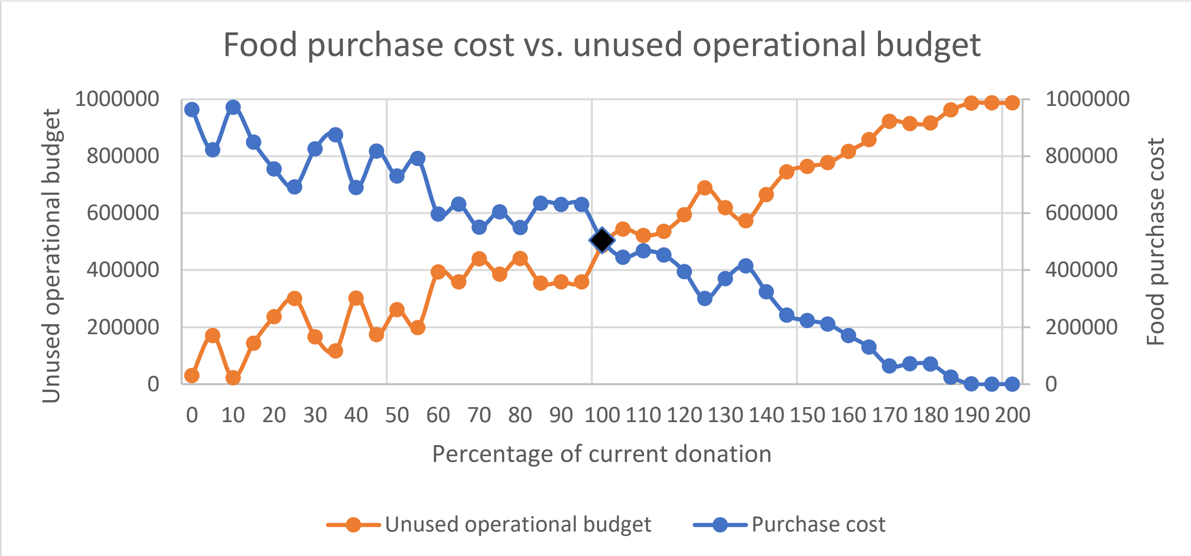


Figure 5.8: Food purchase cost and unused operational budget with variation in donation

As it can be seen clearly that with increase in supply donation from base case, food purchase cost decreases and vice versa. Specifically, when supply donation is zero, maximum amount of food is purchased and unutilized budget is nearly zero but as the supply donation increases unutilized operational budget increases. So, one potential rationale for increase in shortage even after increasing the supply is due to monotonic decrease in purchase of food which ultimately leads to lesser food for distribution and ultimately, shortage increases. It is worth noting that significant part of operational budget is not used as supply donation increases. Food banks can use this operational budget to purchase food but actually food purchase decision depends upon the capacities (storage, transport, manpower) which ultimately depends upon the strategic budget. The strategic budget utilization for all 41 instances is shown in Figure 5.9.

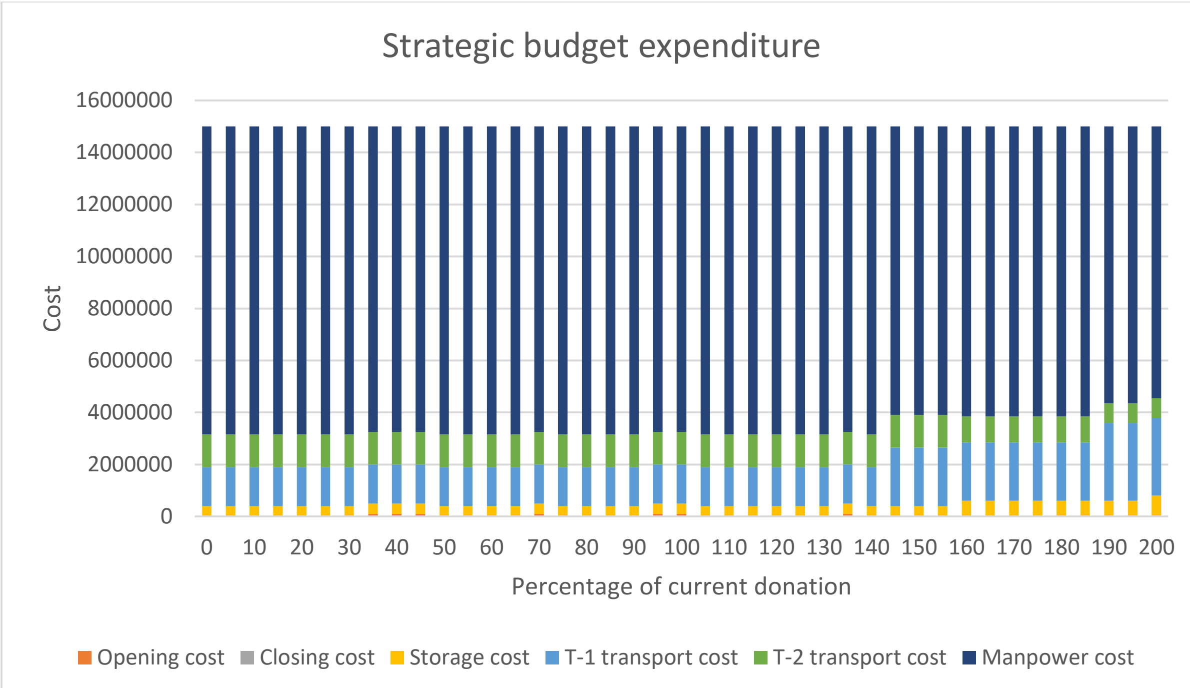


Figure 5.9: Strategic budget expenditure with varying donation

In all these 41 instances, strategic budget utilization is nearly 100%. So, even after having unused operational budget, food purchase amount is constrained by the limited capacities. Moreover, most part of budget is invested on manpower in all the 41 scenarios irrespective of increase or decrease in supply. It can also be drawn that storage cost and tier-1 transport cost increases after 45% increase in supply. The number of manpower hired at both Tier-1 and Tier-2 food banks is given in Figure 5.10.

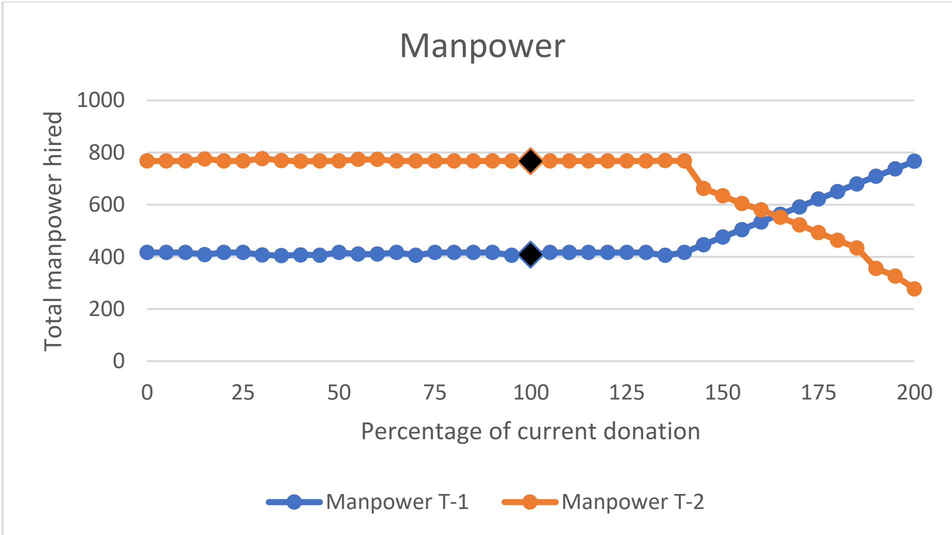


Figure 5.10: Workforce hired at tier-1 and tier-2 food banks with variation in donation

5.5.3. Sensitivity analysis on demand

Food banks problem have an underlying issue of uncertainty on demand side and therefore it becomes consequential to observe the nature and performance of the model as demand increases and decreases. Similar to supply sensitivity analysis, demand is increased and decreased in a step of 5% of the current demand till it becomes double of the current demand (on increasing side) or reaches zero (on decreasing side). Thus, we have created 40 instances of the same model with different demand values. Also, one additional instance corresponds to the base case problem (current demand). The change in objective function value (Shortage) with increase and decrease in supply is plotted in Figure 5.11.

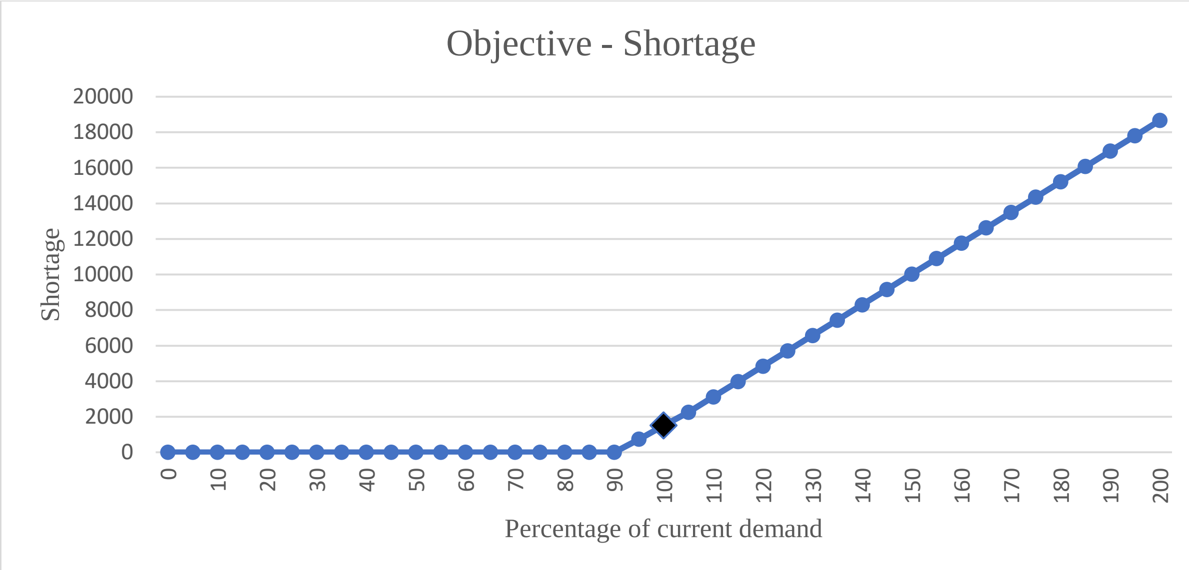


Figure 5.11: Variation in the shortage value with variation in demand

As it is evident form the plot that shortage value for base problem is 1505 units. After decreasing demand by 5% (equivalent to 95% of current demand), the value of total shortage in the system decreases by 51% and after decreasing the demand by 10%, total shortage in the system reaches zero and attains the same status and further decreasing demand cannot impart any change in the value of shortage. On the other side, shortage value linearly increases with increase in demand. For the case of increasing demand, the slope of shortage could be reduced if food purchase cost value also follows the same trend line i.e., it increases with increases in demand. The plot of total purchase cost with variation in demand is plotted in Figure 5.12.

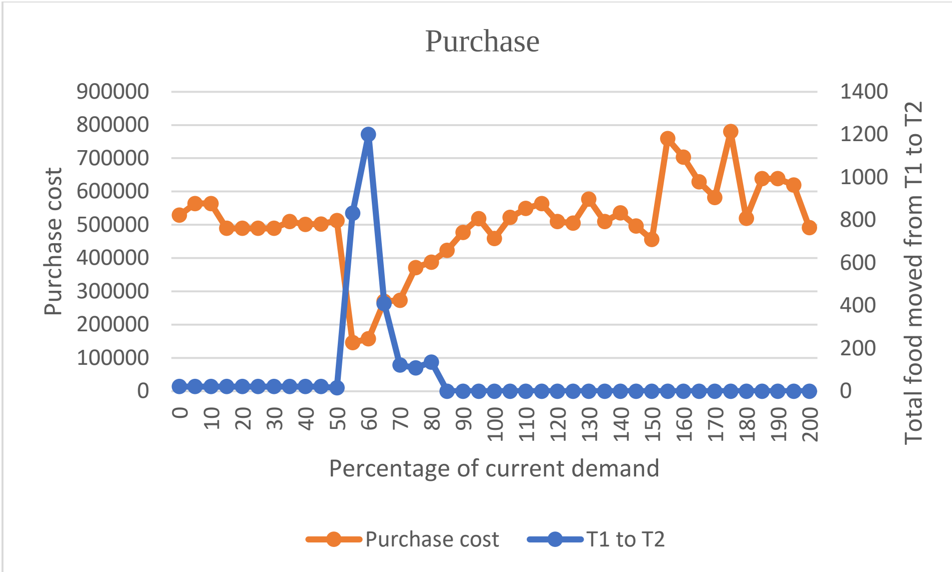


Figure 5.12: Variation in total purchase cost and food transferred from tier-1 to tier-2

The purchase cost varies absurdly with variation in demand. However, some part of it is due to significant increase in food transfer from tier-1 food banks to tier-2 food banks. In Figure 5.12, when demand is between 50% to 85% of current demand the transfer of food from tier-1 to tier-2 food bank increases significantly and after this again attains zero transfer on both increasing and decreasing side. In total food purchase plot, during this interval there is significant drop in the purchase cost which is attributed because of increase in food transfer from tier-1 to tier-2 food banks. Eventually, despite of significant drop in food purchase cost between the interval, 50% to 85% of current demand, the shortage value remains same as zero. It is also worth noting that unmet demand of Priority-1 beneficiaries (tier-2 beneficiaries) contributes more to the overall shortage value. Since, significant food is also transferred from tier-1 to tier-2 food banks during 50% to 85% of current demand interval, these donations assisted in catering out the demand of Priority-1 beneficiaries and resulted in zero shortage value.

It is also interesting to note that during these intervals, more number of tier-2 food banks have been opened. Due to this, expenditure on storage and transportation is relatively more in the instances (50% to 85% of current demand). Specifically, transportation hired at tier-2 food banks increased relatively more. The overall expenditure of strategic budget is given in Figure 5.13. The expenditure pattern between 50 to 80% of current demand is highlighted by square bracket in Figure 5.13.

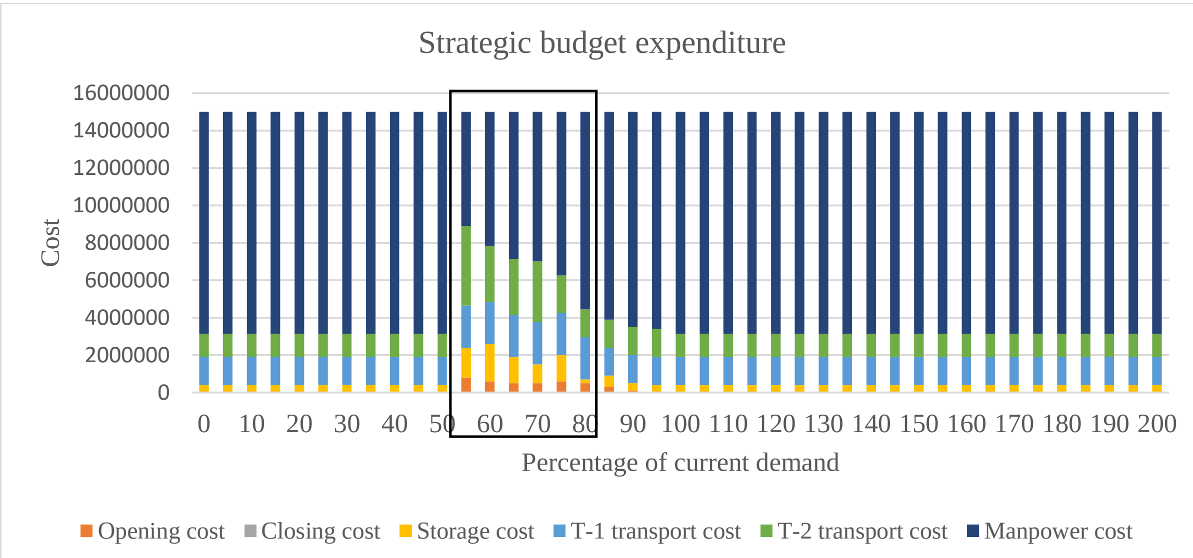


Figure 5.13: Strategic budget expenditure with varying demand

The total manpower cost distribution also varies in the stated interval instances. Since the total strategic budget is limited and in the stated instances, considerable part of it has been invested in transportation, and storage and due to it what is left has been invested in manpower. The manpower distribution for all the 41 instances by varying the demands has been plotted in Figure 5.14.

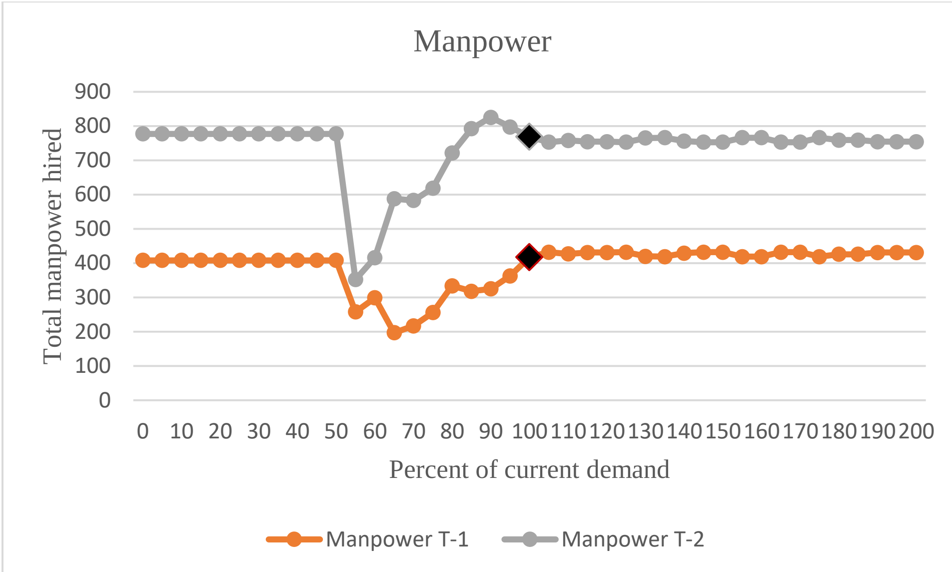


Figure 5.14: Workforce hired at tier-1 and tier-2 food banks with variation in demand

As it can be seen in Figure 5.14, no significant change can be observed on the increase side while there is considerable decrease first, then increase and then achieves a static plot as demand decreases further.

5.5.4. Sensitivity analysis on workforce

The existing food banks have some initial number of volunteers available for carrying out the collection and distribution drives. In the base case scenario, the number of volunteers at each existing tier-1 and tier-2 food banks are 200 (fb1_2, fb1_2, fb2_1, fb2_2). To endeavor the effect of change in initial manpower associated with existing food banks, we executed the entire model with different initial workforce capacity ranging from 0 to 2000 with a step count of 25. It should be noted down that no initial workforce is available at potential location for opening new food banks. To assess the value of shortage with changing initial workforce capacity on existing tier-1 and tier 2 food banks, we plotted the shortage vs. total initial workforce capacity at all existing food banks in Figure 5.15.

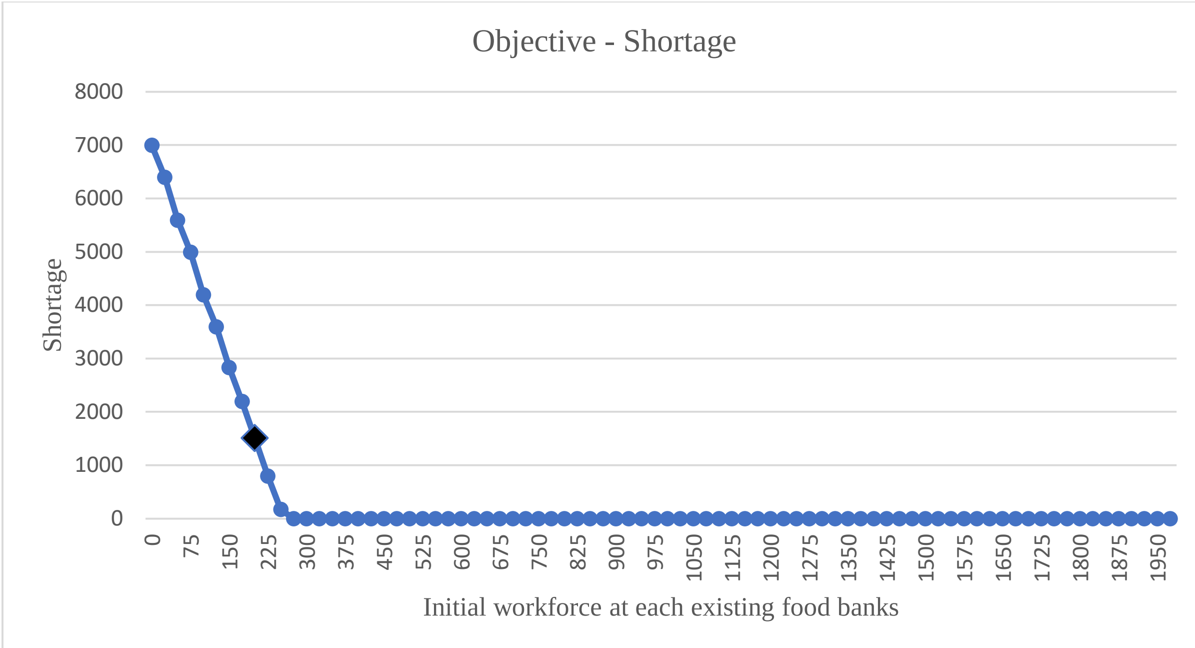


Figure 5.15: Shortage vs variation in initial volunteers at each existing food banks

The value of shortage in the base case (initial workforce at all existing food banks is 200 each) is pointed by black rhombus in all the plots. When initial workforce at all existing food banks is zero, the net shortage in the system is 6993 units. Out of which, shortage contribution for priority -2 beneficiaries (tier-1 food banks beneficiaries) is only 43 units and remaining all is due to priority -1 beneficiaries. For the base case scenario, the total shortage in the system is 1505 units, in which all the shortage value is due to beneficiaries of tier-2 food banks (Priority -1 beneficiaries). The demand of all the tier-1 beneficiaries has been met. Shortage in the system attains a zero value when initial volunteer is further increased to 275 units at each existing food banks. After this, further increase in initial volunteer number do not affects the shortage value of the network and it remains zero throughout. The other consequential front is to analyze the change in number of total manpower hired at existing and new food banks with increase in the existing volunteers and is plotted in Figure 5.16.

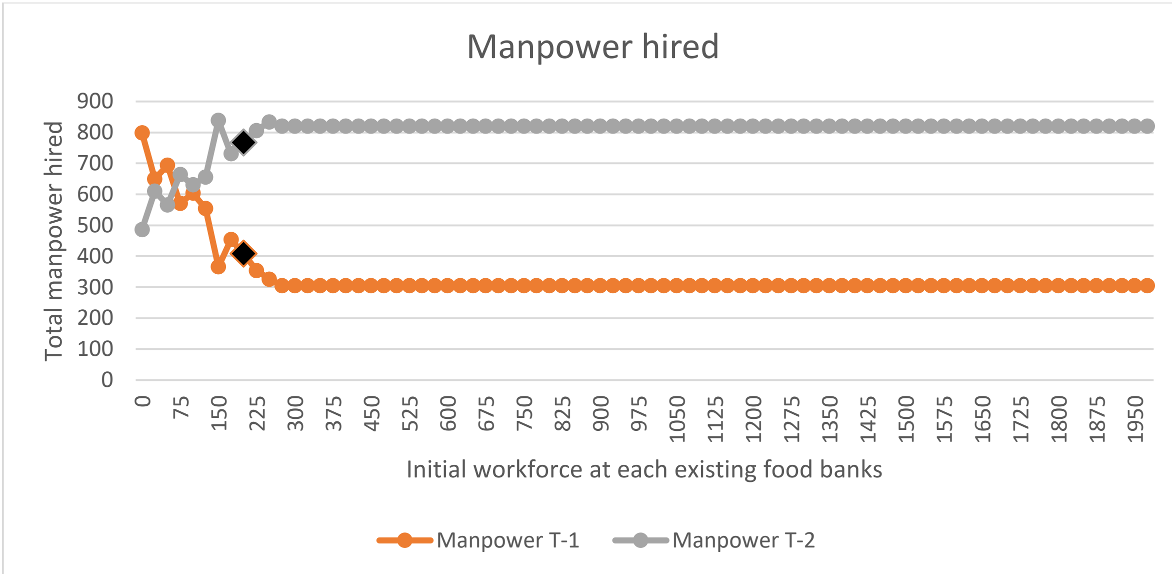


Figure 5.16: Manpower hired with variation in volunteers at existing food banks

In the above plot, till the point 275 (=volunteers at each existing food banks) we can see some variation but after that, plot is nearly constant for both tier-1 and tier-2 food banks. Even if we increase the existing volunteers to 1500, still same number of manpower is hired. In all the cases beyond this point 275, only one new tier-2 food bank is opened at fb2_4 and significant hiring is made (543 units). Following equation (18) and (19), we can derive that manpower hiring is constrained by and existing volunteers and total food available for distribution at existing food banks while for newly opened food banks, manpower hiring decision is only constrained by the total available food at that food bank. This is the reason why newly opened food banks witness significant hiring while there is little scope for existing food banks. Also, our model assumes that volunteers are only associated with existing food banks. So, new food banks must invest in manpower to carry out their operations and therefore increasing volunteers at existing food banks do not impact manpower hiring at newly opened food banks and hence we see the straight-line plot for manpower hiring even after increasing the number of volunteers significantly.

The budget expenditure witnesses some slight variations till volunteers is 275, after that the proportion of budget expenditure is nearly same. Between 0 to 275, total transportation cost for tier-2 food banks increases linearly and then remains constant.

5.5.5. Sensitivity analysis on strategic budget and operational budget

For assessing the performance of overall model with increase and decrease in budget, we carried out sensitive analysis on strategic budget. In the base case scenario, strategic budget value is fixed to 15 million which is highlighted by black rhombus in Figure 5.17. Strategic budget has been varied in the interval from 5 million to 30 million on a step count of 1 million i.e., total 25 instances is created for the same model with different strategic budgets. The value of total shortage in the system with variation in strategic budget is plotted in Figure 5.17.

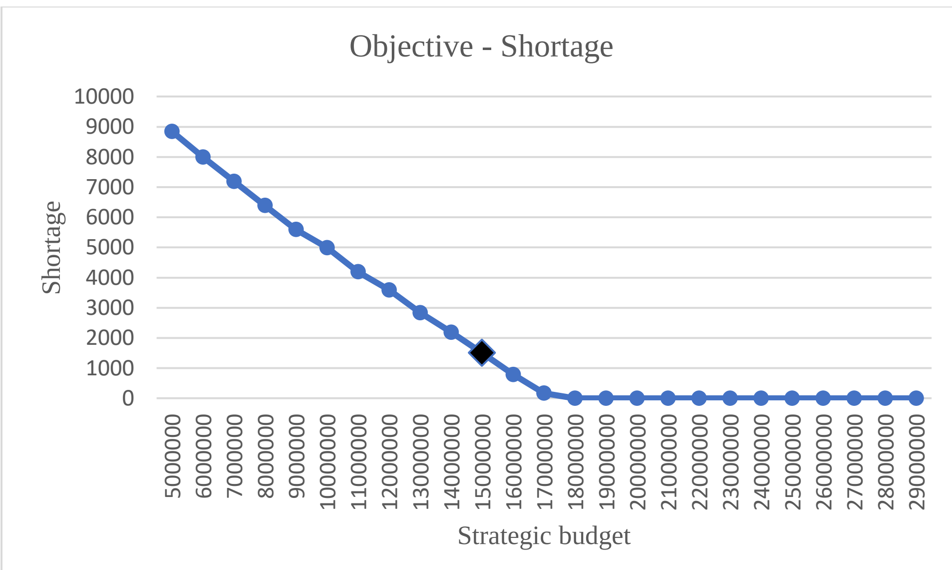


Figure 5.17: Total shortage with variation in strategic budget

The overall plot in Figure 5.17 suggests that, shortage decreases with increase in strategic budget till 17 million, and after that shortage takes a constant value zero throughout. Specifically, the minimum budget needed for shortage to be zero for the base case scenario is 17.67 million which is explained in section 3.5. For capacities like, storage, transportation at tier-1, opening cost not much variation has been observed. The is slight variation in the transportation capacity hiring for tier-2 food banks when strategic budget increases. Moreover, considerable part of strategic budget has been invested in manpower hiring. The total workforce hired at tier-1 and tier-2 food banks with increase in strategic budget is shown in Figure 5.18. Manpower hired at tier-1 and tier-2 food banks firstly increases with strategic cost and then attains a maximum value and remains same for further increase in strategic budget.

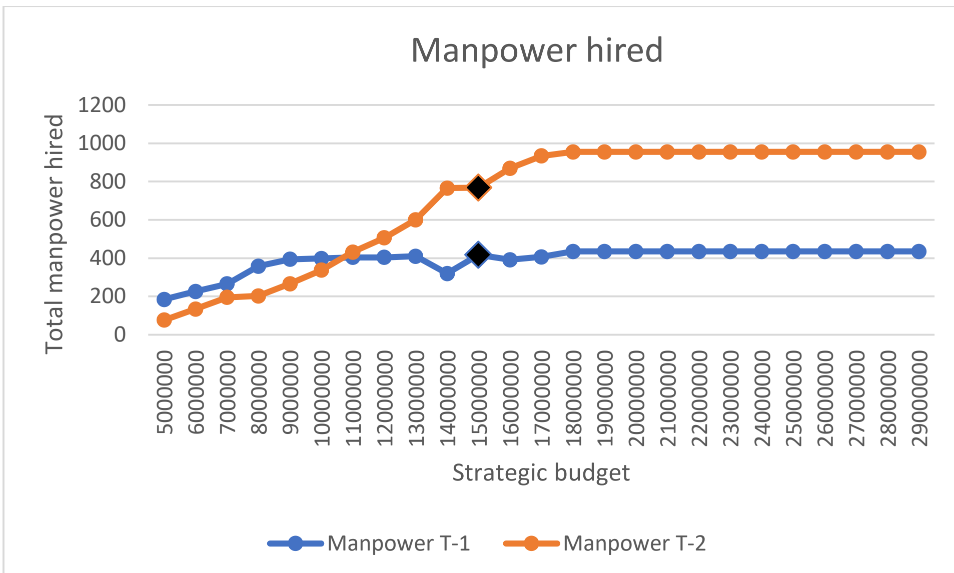


Figure 5.18: Manpower hired with variation in strategic budget

Similarly, the utilization of operational budget firstly increases with strategic budget, attains a maximum value at 11 million (32%) and then remains unchanged with further increase in strategic budget.

To analyze the effect of variation in operational budget on shortage, sensitivity analysis is carried out. The operational budget is changed within interval 50000 to 2 million on a step count of 50000 thus creating 40 instances of the shortage model (P) with changing operational budget. The plot of shortage with increase in operational budget is shown in Figure 5.19.

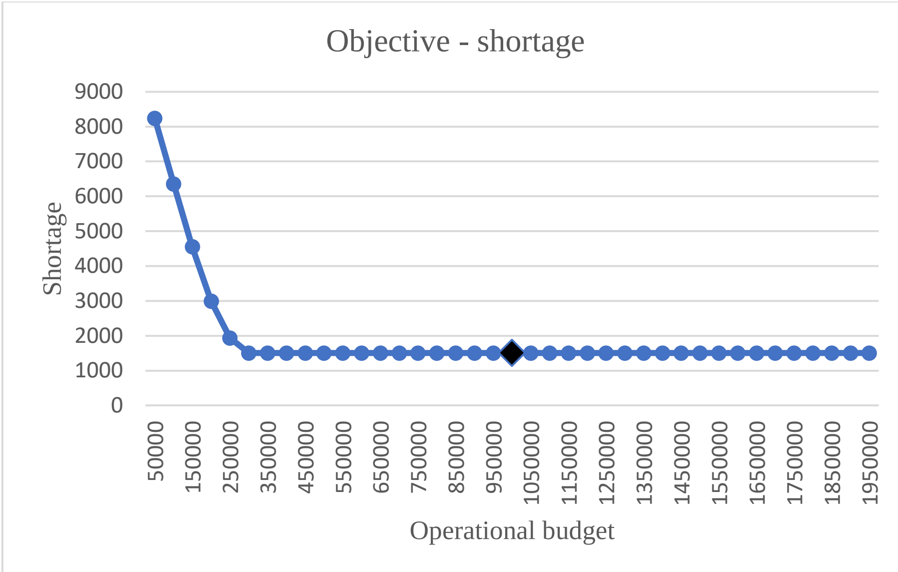


Figure 5.19: Total shortage with variation in operational budget

The operational budget set for base case scenario is 1 million. As operational budget is decreased from 1 million, the value of shortage remains same till operational budget 30000. Further decrease in operational budget leads to exponential increase in shortage. Moreover, shortage remains same when operational budget is increased from base value. It is also worth noting that minimum operational budget for the total shortage of 1505 units is 30000.

5.5.6. Sensitivity analysis on Total Cost minimization model (P5)

This model minimizes the total cost incurred in opening, closing, installing/expanding storage capacity, installing/expanding transportations, hiring manpower, purchasing food and travelling cost. In the objective function of model P5, we have penalized the total shortage to ensure all the demand do not turn into shortages. The value of penalty chosen for the base case experimentation is 5000. For sensitivity analysis, the penalty value is varied in two intervals [0,10000] on a step count of 1000 and [11000, 91000] on a step count of 10000. So, there are 20 instances with varying penalty values. The plot of total cost and total shortage with different penalty values is given in Figure 5.20.

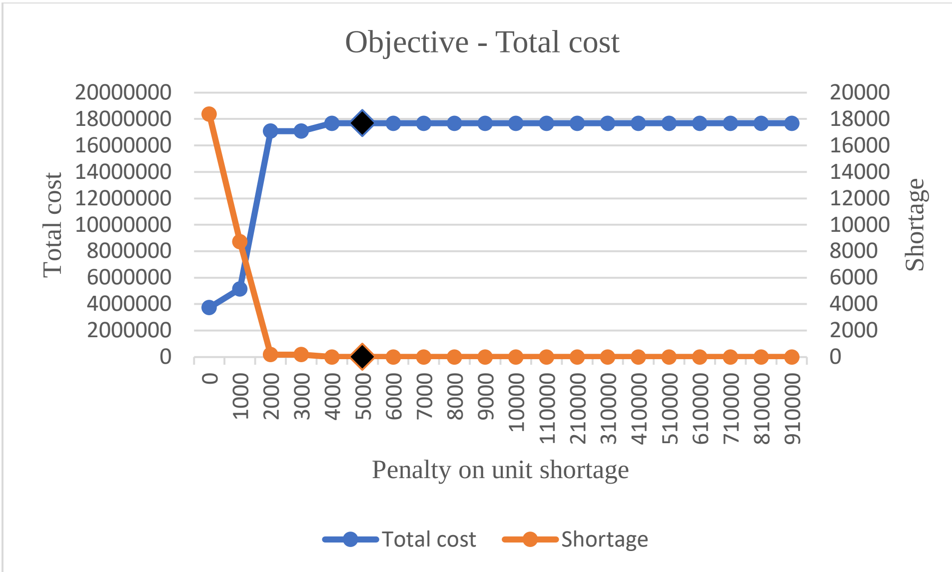


Figure 5.20: Total cost and Total shortage with variation in penalty value on shortage

The value of total shortage monotonically decreases for penalty value in range [0, 3000] inclusive. After this, total shortage value is zero throughout all the penalty values. The minimum total cost for zero shortage is 17.67 million.

5.6.Conclusion

This paper presents a food bank supply chain network design problem motivated from Indian food banks. Indian food banks have a unique architecture that involves operation of food banks in some hierarchy. These hierarchical division is based on type of donors, type of food, scale of operation, and type of beneficiaries. Based on these factors Indian food banks operates in two hierarchies – Tier-1 food banks and Tier-2 food banks. Basically, tier-1 food banks operate on large scale having storage facilities with big firms/industries as their donor and distribute the donated food to agencies or beneficiaries who are receiving food assistance from other sources as well and therefore supplements the already existing process. Tier-1 food banks provide food assistance to tier-2 food banks to sustain their operations. Tier-2 food banks are highly constrained by resources, receives donation mostly for leftover food (ready-to-eat) from donors like catering agencies, restaurants, individuals and distributes beneficiaries who are more prone to hunger. The food assistance to these beneficiaries is usually primary source for their sustenance. This type of architecture has not been endeavored in the literature for food bank supply chain network design problem. The major decisions involved in network design problems are opening a food bank at potential candidate location, closing an existing food bank, installing and expanding storage capacities at existing tier-1 food banks, installing and expanding transport capacities for existing and new food banks, hiring manpower for existing and new food banks, amount of food to be purchased and decisions related to travelling. Food is principal entity in food bank network design problem and good nutrition value in food is crucial for beneficiaries. Food banks strive to provide nutritious meal to the beneficiaries under resource constraints. The requirements of food vary from beneficiaries according to their gender and age. To the best of our knowledge, this is the first study which integrates food bank network design problem and nutritional value of food according to age and gender in one model. Specifically, we tried to ensure that the recommended dietary nutrition should be for each beneficiary type with the donated and purchased food. Thus, we ensure hunger alleviation by distributing the nutritious meal to end beneficiaries according to their dietary requirements. The paper proposes a mixed-integer linear programming model and its variation for designing the supply chain network of food bank considering unique architecture and nutritional requirement. The base model proposed have an objective function for minimizing the total shortage in the network. The variations of the base model incorporate several other objectives and/or constraints related to food banks according to its requirement, such as equitability in distribution, total cost minimization, weighted shortage if we want to prioritize a particular type of beneficiary, perfect equity, and so on. Essentially, 10 variations have been proposed in this study. The solution of these variations of the base model will provide a bird's eye view which could be utilized to analyze the variation and select the most suitable one according to requirements.

The other consequential contribution of this works concerns the development of case study on Indian Food banks operating in national capital of the country. In the proposed study several Indian Food banks have been contacted through electronic medium to understand their mode of operation and to fetch data for network design problems. The base model and its variation have been executed on the case data and results are provided. Some important insights have been generated from the results all the models. Nearly in all the models, manpower is highly constrained in Indian food banks and considerable portion of strategic budget (77% to 79%) should be spent on hiring manpower irrespective of the objective function (total cost minimization, shortage, equity and so on). No closing decisions have been found in all the models which is due to the large number of beneficiaries and relatively less food banks are available to cater their need. Due to the central location and large number of priority -1 beneficiaries, manpower hiring is relatively more in tier-2 food banks especially on fb2_2. Similarly, more transportation resources at tier-2 food banks are needed due to the above reason. Moreover, most collected and purchased food is "Indian bread" and "banana".

We propose a comprehensive sensitivity analysis on the base model for the various uncertain and deterministic parameters used in the model. The results of sensitivity analysis give necessary insights to minimize the shortage. To reduce the total shortage to zero, it is advisable either to increase the strategic budget to 17.6 million (which is initially 15 million) or increase the associated volunteers at each existing food banks to 275 (which is initially 200). Furthermore, increasing operational budget do not contribute to minimization of shortage after a certain value (1505 units) and the minimum operational budget needed for this threshold value of shortage is 0.3 million. Specifically, investing in operational budget need not reduce the total shortage in the system. For the total cost minimization model, the optimal value for the penalty factor used for penalizing shortage in the system is 4000 units.

The contribution of proposed work is multi-fold and we endeavored to include the important aspect related to nutrition and hierarchy, However, we have not incorporated uncertainty in food donation and demand of beneficiary in our study. A robust model could be developed in the future to remove this limitation.