Chapter 1: Introduction

India is the most populous country in the world and contributes 17.7% of the total world's population (The World Bank, 2023). Ensuring the production and availability of food for such a mammoth population of the country has always been a challenge. In the early decades after the independence in 1947, the country faced an acute shortage of food grains. In India, the production of food grains in the year 1950-51 was 50.82 million tons and the yield were 522 Kg per hector. With a population of 361 million, the per capita net availability of food grains in the year 1951 was meager 144.1 kg (Agricultural Statistics at a Glance, 2022). The production and yield of food grains in the country shown a steady but insufficient increase till mid 60's. The import of major food grains (rice and wheat) during this period were staggering (as high as 8.5 million metric tons) and shown a continuously increasing trend. On the contrary, the export of the food grains was minimal. The situation begun to change majorly due to the Indian government's agricultural policies and the green revolution in the sixties. After Independence, land reforms were done extensively which primarily focused on annulment of intermediaries that had caused decreased employment and productivity (Tripathi & Prasad, 2010). The government backed small farmers by compensation and intermediaries by pension for their lands. Beside this agrarian reform, several other initiatives were taken by government such as strengthening of rural credit institutions, development of irrigation projects and cultivated area. Additionally, the major policy paradigm shift occurred in agriculture sector by the introduction of minimum support prices, subsidies and procurement, storage and distribution of food grains (Arora, 2013). The intensive agriculture methods adopted under the gamut of the green revolution during mid-60's to 80's such as using good quality high yielding variety seeds, pesticides, greater use of irrigation facilities, use of fertilizers and agro-

chemicals was a game changer. After this phase of green revolution, reforms were essentially based on effective use of information technology. The government of India had launched several programmes and schemes with a target to increase the agriculture productivity and double the farmer's income. The schemes and initiatives include National Food Security Mission (Singh & Grover, 2015) to ensure the availability of five basic components rice, wheat, pulses, coarse cereals and commercial crops, *Rashtriya Krishi Vikas Yojana* that targets making India self-sufficient for oilseeds, pulses, palm oil and maize (Kalamkar & Shroff, 2010; Tinde et al., 2016); *Pradhan Mantri Fasal Bima Yojna*, a crop insurance scheme for farmers to provide insurance that cover crop loss or damage, stabilises income of farmers, ensures food security by enabling flow of credit to agricultural sector (Tiwari et al., 2020).

It can be seen that the yield of food grains (kg per hector) got doubled from 1950 to 1980 and further quadrupled till 2010. The import of the major food grains become dormant and the exports shown a remarkable increase after 1990's. Currently, the net per capita availability of food grains has been raised to 177.7 kg per year. Apart from these, India is the world's second-largest producer of wheat, rice, sugarcane, cotton, groundnuts, and the world's largest producer of milk (*FAO in India,* 2019). Total food grain production in 2017-18 is recorded as 277.49 million tons (Agricultural Statistics at a Glance, 2022). Some of these milestones are depicted in Figure 1.1. To summarize, the green revolution and government's agricultural policies and various initiatives resulted in increase in the productivity in Indian agriculture and by large, it contributed in solving the problem of availing the food grains to its population by reaching a state of self-sufficiency (Kumar et al., 1998).

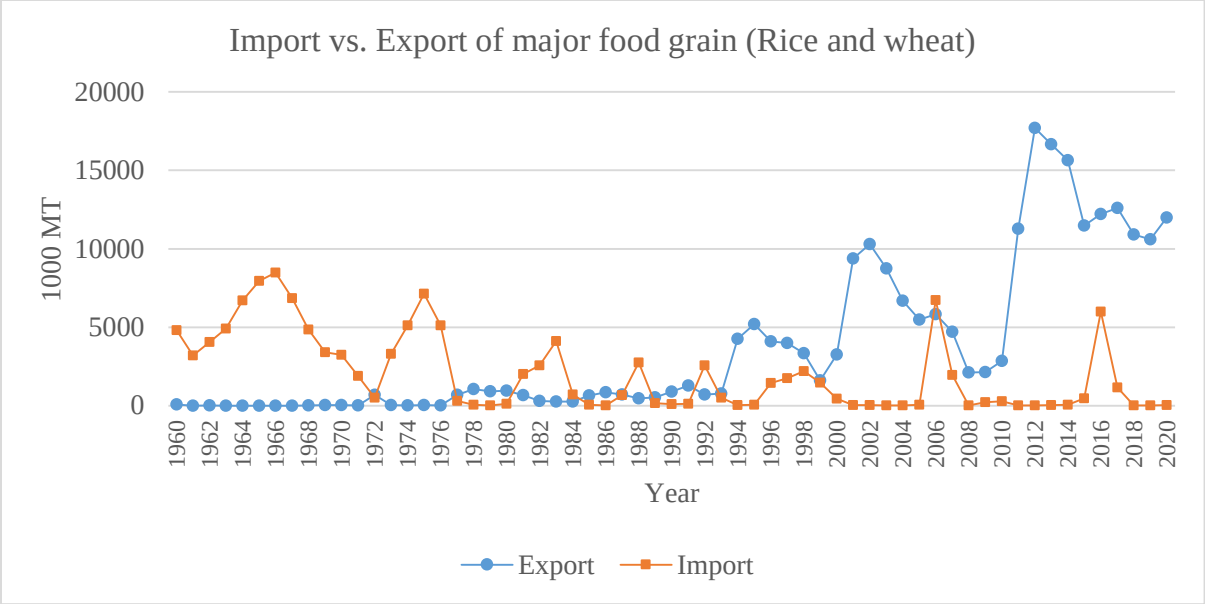

Figure 1.1: Import vs. Export of food grains (rice and wheat)

In spite of this promising agricultural developments in terms of productivity and self-sufficiency, the picture of food security in the country is not so promising. India is ranked 111th out of 125 countries in the (*Global Hunger Index*, 2023) with the reported "serious" level of hunger in the country. According to the report of the State of Food Security and Nutrition in World by Food and Agricultural Organization of the United Nations, 194.4 million people are undernourished in India (*FAO in India*, 2019). Further, the average per capita availability of the food grains in India in last five years is 177.12 kg which is very less as compared to the countries such as Bangladesh, China and USA where the per capita availability of the food grain in 2015 was 200, 450 and 1100 kg, respectively (Down to Earth, 2018). Thus, the problem of hunger, malnutrition and the overall food insecurity co-exists in India in a paradoxical environment of excess agricultural produce. Various measures have been taken by the government from time to time to fight against hunger and eradicate food insecurity from India. The public distribution system (PDS) is the major example of it. India has the largest PDS in the world that targets distribution of food grains at a nominal price to the needy people

(Tanksale & Jha, 2015). Several other schemes such as National Food Security Act, (2013) and Mid-day meal scheme have been proposed and in action from a long time in the country. However, due to several factors such as lack of infrastructure, limited resources, operational inefficiencies, malpractices, and exploding population, the majority of these schemes have underachieved the goal of eradicating hunger and to serve the economically deprived people.

The other important dimension in the fight against hunger and undernutrition is work carried out by several non-government organizations (NGOs) or individuals which is complementary to the government programs and schemes, and play a crucial role in elevating the overall food security (Brinkerhoff et al., 2007). This work concerns the organizations serving as food rescue units'/food banks that deal with surplus food recovery/food donations and distributions. Food banks can be defined as a place where people such as individuals, farmers, corporates, food industries, hotels, restaurants give their donation, which can be further transferred/distributed either to charitable agencies or directly to people in need. The definition of food banks varies for different stakeholders involved in it. For people who donate food: food bank is a work of charity; For restaurants, farmers, hotels, food industries, supermarkets: food bank is a way to put unused product and leftover food into use; for volunteers: it is a medium to practice philanthropy and for people who receive donation: food bank is sometimes a need to get away hunger and sometimes a sustenance and comfort source (Brown, 2019). In other words, we can say that food banks work as a bridge between food-insecure people to people who have abundant resources. A typical food banking system comprises of five entities – donors, beneficiaries, food, transportation and storage resources and volunteers or employees as given in Figure 1.2.

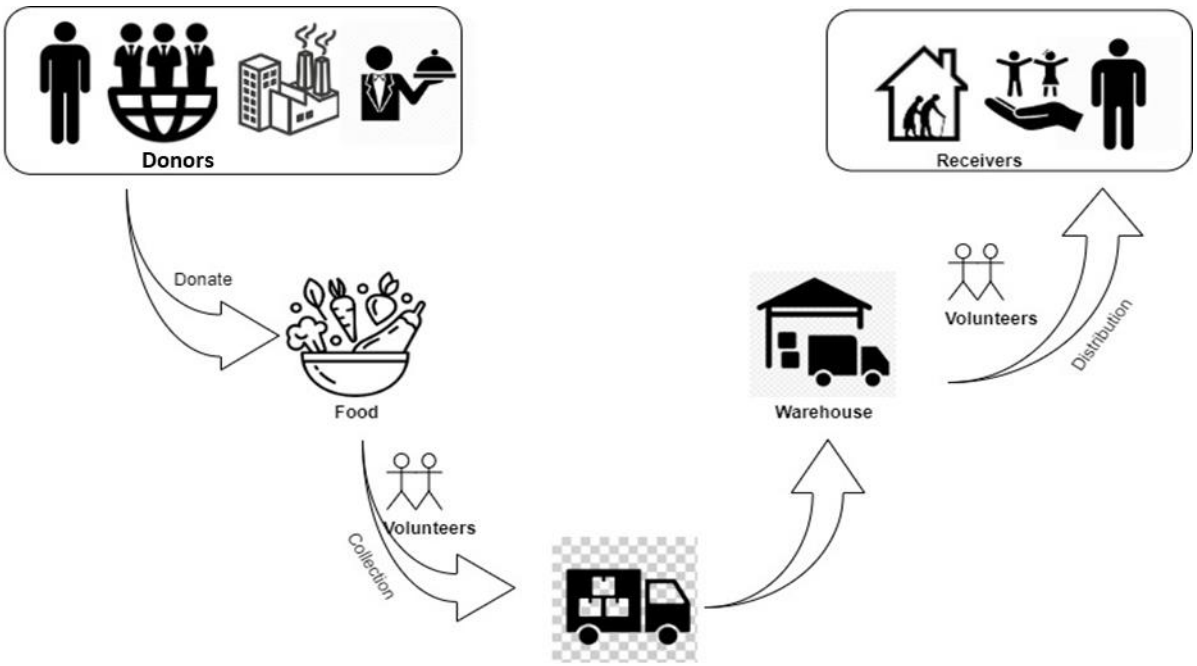

Figure 1.2: A typical Food banking system

Another important aspect concerned with food banks is the food waste reduction. It is well-known that a significant amount of food is wasted in the food supply chain. Most of the times, the condition of these food is suitable for human consumption but have limited consumer appeal and therefore these foods are discarded and they end up in landfills. Food banks receive the supply from donors such as supermarkets, farmers, hotels and restaurants, the food donated by these donors are sometimes is about to reach its expiry dates, or have very low sales rate. In case of hotels and restaurants, the donated food is mostly the leftovers or surplus food in edible condition and eventually these food ends up in bins without proper recovery and distribution mechanism.

1.1.Food banks: Global Overview and Local Snapshot

The operating procedure, organizational structure, and hierarchy of food banks differs from country to country. In some countries, food banks are established entities and their modus operandi and overall structure is highly organized and follows standard operating procedures.

On the other hand, countries with recent food bank phenomenon witness unorganized structure and ways of operating. For instance, Feeding America – a United States based organization has an interlinked network of partner agencies that include more than 200 food banks, over 60,000 partner agencies, soup kitchens, emergency shelters and food pantries. In the past year's annual report, they cited that they successfully rescued 3.96 billion pound of food with retailers, manufacturers and growers (Feeding America, n.d.). In addition, it campaigns for legislation that address the underlying causes of hunger and raises awareness about the pervasive problem of food insecurity in the US. Similarly, Canadian food bank network consists of 10 provincial associations covering their 4750 affiliated food banks and communities. The scope of Canadian food bank network expands beyond food and targets child hunger, innovation and other dimension of social issues (Food Banks Canada, n.d.). In UK, more than 1200 food banks out of 2000 plus food banks in the country are run by the Trussell Trust. The *Rete Banco Alimentare* (Italian Food Bank Network) has similar structure in Italy. Thus, it can be stated that the food banks operating in these countries have a well-defined network and they are managed/controlled by a dominant parent organization. On the other hand, the concept of Food Bank in India has been ingrained only in the last decade and is still in a nascent stage. With the inception of the first food bank in India in 2009, around 187 food banks are operating at present in 23 states and 4 union territories of the country (Indian Food Sharing Alliance, n.d.). Most of the food banks/non-profit organizations involved in food rescue operations in India are operating in silos and lacks coordination among them. Another distinguishing feature among the Indian food banks and their counterparts in other countries is the infrastructure and nature of the food. It can be seen that the food banks operating in western countries have well-furnished refrigerated warehouses which provides them ability to collect,

store, sort, pack and deliver the food packets whereas most food banks in India work on front-end model. That is, they are primarily collecting the cooked food from the donors and distributing it to the needy immediately upon recovery. Thus, there are several characteristics and challenges pertaining to the Indian scenario that distinguishes the Indian food banks from others.

1.2.Barriers to the adoption of food banks in India

In many impoverished regions, food insecurity remains a pressing issue, with millions of people lacking consistent access to sufficient, safe, and nutritious food. As a response to this crisis, food banks have emerged as a vital mechanism for addressing hunger and reducing food waste. These organizations collect surplus food from various sources, including farms, manufacturers, retailers, and individuals, and redistribute it to those in need. The concept of food banks is rooted in the principles of social equity and sustainability, aiming not only to alleviate hunger but also to reduce the environmental impact of food wastage.

However, the successful operation of food banks in impoverished nations is fraught with numerous challenges. Limited infrastructure, financial constraints, and logistical difficulties often undermine their ability to efficiently collect, store, and distribute food to vulnerable populations. One of the primary challenges is the inadequacy of resources, encompassing financial constraints, limited manpower, and insufficient infrastructure. The constant struggle to secure funding and volunteers hampers the operational efficiency of food banks, hindering their ability to reach vulnerable communities effectively. Legal and regulatory hurdles pose another significant challenge. Ambiguous or lacking legislation related to food donation and redistribution creates obstacles for food banks in collecting and distributing surplus food. The need for a clear legal framework, supportive policies, and incentives to encourage donations is

crucial for the seamless functioning of food banks. Furthermore, the inherent uncertainty in the supply and demand for donated food adds complexity to food bank operations. Fluctuations in donations, coupled with varying demands from beneficiaries, necessitate the development of robust models and strategies to address these uncertainties effectively. Infrastructure-related challenges, including inadequate storage facilities, transportation constraints, and logistical issues, impact the timely and efficient distribution of food. The lack of coordinated planning and collaboration among food banks exacerbates these challenges, leading to suboptimal performance and reduced effectiveness in combating hunger.

Despite these challenges, food banks present a promising solution to both food insecurity and food waste. By redistributing surplus food that might otherwise end up in landfills, food banks help reduce the carbon footprint associated with food disposal. This dual benefit has led to increasing recognition and support for food banks from various sectors, including industries, philanthropists, researchers, and practitioners who are committed to promoting food security and environmental sustainability.

Nevertheless, the effectiveness and scalability of food banks are often limited by the very challenges they seek to overcome. These operational hurdles not only reduce the impact of food banks but also restrict their capacity to expand and reach more people in need. Therefore, it is crucial to systematically study these challenges to better understand their nature and severity. By modeling and addressing these issues, food banks can develop more effective strategies to enhance the growth and adoption, ensuring their long-term success in combating hunger and food waste.

1.3. Optimal distribution of food

Food banks are non-for-profit humanitarian organizations that assist in alleviating hunger and ensuring food security through surplus food recovery and redistribution to the unprivileged section of society (Dubey & Tanksale, 2022). Food banks procure surplus food from institutional and individual donors, utilizing two main distribution models: direct delivery to beneficiaries (front-end) or through charitable agencies. They face significant operational challenges, including complex processes of collection, sorting, processing, distribution within tight timeframes, and storage, all exacerbated by limited resources such as manpower, financial support, and logistics infrastructure.

Recent studies highlight that Indian food banks struggle with inadequate storage, transportation, and planning, which hampers their efficiency. To maximize their impact, food banks must optimize resource use and operational planning, particularly in transportation scheduling, to serve the maximum number of beneficiaries at minimal cost. In the operational framework of food banks, there exists a diverse set of recipient locations encompassing charitable agencies, old-age homes, orphanages, slum areas, etc., to which food must be efficiently delivered as shown in the “receivers” of Figure 1.2. This delivery process is facilitated by a fleet of vehicles. However, the food is not always readily available at a central depot; it often needs to be retrieved from diverse locations such as hotels, supermarkets, restaurants and catering service providers as shown in the “donors” of Figure 1.2. The operational dynamics of food banks, specifically the collection and distribution of surplus and leftover food, can be mathematically modeled as a variant of the Vehicle Routing Problem (VRP). The Vehicle Routing Problem (VRP) is a classic combinatorial optimization problem

that includes calculating the most efficient routes for a fleet of vehicles to serve a set of clients while adhering to certain set of constraints depending upon the problem (Sharma et al., 2018). Over time, numerous variations of the VRP have arisen to satisfy unique real-world conditions and requirements (Gutiérrez-Sánchez & Rocha-Medina, 2022; Soares et al., 2024). These variants include the Capacitated VRP (CVRP), Vehicle Routing Problem with Time Windows (VRPTW) and the Multi-Depot VRP (MDVRP), Split Delivery VRP (SDVRP), Pickup and Delivery Problem (PDP). The Capacitated Vehicle Routing Problem (CVRP) is one in which each vehicle has a restricted capacity to transport items, and the aim is to identify a set of routes that minimizes overall cost while meeting capacity limitations (Sluijk et al., 2023). The Pickup and Delivery Problem (PDP) extends the VRP by requiring commodities to be transported from pickup to delivery locations (Koç et al., 2020). This version is popular in instances where objects must be picked up from one location before being transported to another. The Multi-Depot Vehicle Routing Problem (MDVRP) includes various depots which aims to identify the best distribution of fleet of vehicles available at the depots to service customers while reducing total costs (Montoya-Torres et al., 2015). The Vehicle Routing Problem with Time Windows (VRPTW) integrates time limitations by defining time windows when customers must be serviced (Sluijk et al., 2023). This adds another element of complexity since routes must be produced in a way that ensure the timely deliveries. Split Delivery variant of VRP corresponds to splitting the delivery demands of customers across multiple vehicles due to a number of reasons not limited to constrained vehicle capacities (Sluijk et al., 2023). These variations result from the different needs of real-world logistics and transportation scenarios. Researchers and practitioners use a variety of optimization approaches, heuristic algorithms, and metaheuristics to meet the unique issues presented by each VRP variation.

Notably, food banks operating on the front-end model engage the same fleet for both the rescue and redistribution of surplus or donated food. Consequently, this logistical challenge aligns with the characteristics of the Vehicle Routing Problem (VRP) with pickup and delivery components. Moreover, considering the perishable nature of donated food, particularly in the case of ready-to-eat items, there is a critical need for prompt distribution to beneficiaries on the same day or within a few hours. Concurrently, donors adhere to stringent time intervals for the collection of donated food. Addressing these temporal constraints necessitates the incorporation of time windows in the planning of food item collection and distribution operations. These specific characteristics of food banks are under explored and it requires a tailored approach to address these realistic intricacies into the problem conceptualization phase. Considering these intricacies while addressing the routing problem will help in producing quality routes that matches with the requirements of food banks with very limited manual interventions. Efficient routes will enable food banks to perform their daily activity effectively.

VRP can have diverse set of objectives depending upon the requirements. Most common objectives associated with solving VRP is minimization of total transportation cost, total distances travelled, travel time, better vehicle utilization, reduced carbon emissions. On the contrary, in the context of food banks there could be additional set of objectives that is not directly linked with cost minimization such as equitable distribution, maximizing the fulfillment of delivery demand (demand of beneficiaries), minimization of number of vehicles used for carrying recovery and distribution of donated food. Due to the variety of economic and social objectives, it becomes consequential to incorporate the multiple objectives into the problem conceptualization to map the problem definition more closely with the real-time

scenario. Encompassing multiple objectives based on real scenarios will benefit the system specially if the objectives under consideration have underlying trade-offs. For example, objectives such as maximization of demand fulfillment and equitable distribution to beneficiaries have trade-offs which can lead to solution that have improvement in one objective while deterioration in other. To the best of our knowledge, multi-objective frameworks have limited exploration in the context of food banks and therefore we need to devise appropriate robust methodology that can solve the problem considering this multiple conflicting objective in real case. Incorporating a multi-objective framework allows for a comprehensive examination of the intricate trade-offs involved in food bank operations.

In conclusion, the operations of food banks, encompassing the collection and distribution of surplus food, can be rigorously modeled as a specialized variant of the Vehicle Routing Problem (VRP). This modeling approach necessitates the incorporation of specific requirements, such as the perishable nature of food items, stringent time windows for both collection and distribution, multiple depots. By adapting the VRP framework to these unique operational requirements, food banks can achieve greater efficiency in their logistical processes, thereby enhancing their capacity to serve beneficiaries and minimize operational costs.

1.4.Network design of food banks in India

The United Nations' Sustainable Development Goal 2 (Zero Hunger) aims to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture by 2030. However, global food insecurity is worsening, with 828 million people affected by hunger in 2021 and projections indicating that 8% of the world's population will still be hungry by 2030. Addressing the strategic aspect of problem can enrich the overall effectiveness of the food

banking system. The network design of food banks is critical to ensure the efficient and successful delivery of food to people in need and eliminate the myopic planning process. The food bank supply chain involves a network of donors (including corporations, industries, farmers, hotels, restaurants, catering agencies, and individuals), beneficiaries (such as charitable agencies, old age homes, orphanages, homeless individuals, and slum dwellers), food types (cooked and packaged food), and operational entities (front-end and back-end food banks), supported by a workforce of volunteers and employees as shown in Figure 1.2. Front-end food banks focus on immediate food recovery and redistribution, primarily dealing with cooked food and lacking adequate storage facilities. In contrast, back-end food banks possess sufficient storage, including refrigeration, and handle both cooked and packaged food as shown in Figure 1.2. The operations of food banks are primarily sustained by food and monetary donations, with monetary contributions often insufficient, leading to a heavy reliance on volunteers. The availability of volunteers is uncertain, and their absence can disrupt food collection and distribution, resulting in food waste. From a network design perspective, the supply chain of food banks can be optimized to enhance efficiency and reduce food waste. Food banks align with two key SDGs: "Zero Hunger" (SDG 2) and "Responsible Consumption and Production" (SDG 12), positioning them as a sustainable solution to hunger. By improving the design and management of food bank networks, including optimizing donor and beneficiary connections, enhancing storage and transportation logistics, and ensuring reliable volunteer availability, food banks can play a vital role in reducing food insecurity and waste, thereby contributing to global sustainability efforts.

Food banks should be strategically placed within a network based on geographic regions, population density, and places with acute hunger. Such considerations in the network design

model could allow for assisting decision maker on optimal location for opening a new food bank, on where to expand the resource capacities of the existing food banks or on where to close the existing food banks. The network design could be further enriched by incorporating the notion of nutritional requirement of beneficiaries according to their age-gender profile. To the best of our knowledge, despite of food being central entity in the system, its characteristics pertaining to nutritional value of the donated food have not been incorporated. A well-designed food bank network should consider the nutritional value of donated or purchased food products, aiming to provide beneficiaries, food that meets recommended daily consumption standards. Incorporating the existing tiered structure of food banks into the network design phase can significantly enhance the model's alignment with real-world scenarios. By explicitly addressing the distinct characteristics associated with different tiers of food banks, the model introduces an additional layer of complexity. However, this complexity can be leveraged to optimize the utilization of human and transportation resources, thereby ensuring more efficient and effective food distribution. Integrating tier-specific attributes into the network design allows for a more accurate representation of operational constraints and resource allocation strategies, ultimately improving the overall effectiveness of food distribution networks in reaching their intended beneficiaries. Moreover, it aids in making informed budget-related decisions, optimizing the allocation of financial resources to meet the demands of various tiers within the network.

Overall, a well-planned food bank network design goes beyond mere distribution logistics; it becomes a strategic tool for addressing nutritional aspects of different geographical areas, optimizing resource allocation, and enhancing the impact of food banks on the communities they serve.

1.5.Motivation

Food banks are established in response to alleviate hunger rather than being the result of a deliberate planning process. This reactive mode of settings has myopic view on the entire planning horizon that leads to adverse consequences on the overall performance of food banks. The overall operating process of food banks under reactive planning suffers with in-efficient and in-effective process, poor utilization of resources, high risks of breakdown or failures and sub-optimal solutions. These underlying problem affects all the entities involved in the food banking ecosystem. The most affected entities of these in-effective system have been the beneficiaries of the food banks as these poor utilization of resources leads to unplanned distribution of collected food. As a result, sometimes food banks end up distributing either less or more than the actual required amount of food. The most frequent case is distributing less than required food since most of the times the collected amount of food do not meet the requirements of food banks. The most consequential aspect that affect the operations of food banking ecosystem is the uncertainty in food donation and demand. The amount of food donations depends entirely on the donors. Due to several factors associated with the system of donors' business, such as high and low demand of products, the amount of food donation varies. This variability leads to potential disruptions in the day-to-day activities of food banks. Sometimes, due to larger amount of food donation, food banks require more number of volunteers to collect, handle and distribute the donated food. Unavailability of volunteers could cause poor collection and distribution activities. Similar set of problem can be seen on the demand side due to uncertain donations and variability of demands of the end-beneficiaries. These fundamental issues persist prominently in developing countries like India. The type of food preferences poses a huge problem in the daily collection and distribution of food. The

other pertinent issues such as various region-specific characteristics of operating food banks add a layer of complexity to the entire system. Most food banks in India collect food from the donors and distribute immediately due to the type of food (mostly cooked meal that stales rapidly). The intrinsic characteristics of Indian food banks such as collecting and distributing cooked meal which is susceptible to rapid staleness, huge reliance on volunteers for carrying out collection and distribution activities, inappropriate storage measures for cooked food, limited resources demand sophisticated algorithms that can undertake these characteristics. These characteristics not only distinguishes Indian food banks from other, but they also pose a potential need to study the challenges of food banks, endeavor the roadblocks and facilitators, avenues for improvement of food banks operations typically in Indian scenario. Moreover, these food banks need to effectively plan their limited resources to carry out their collection and distribution activities smoothly. This could be achieved by dedicated planning and support using state-of-the-art techniques pertaining to food banks in the domain of routing, resource planning, network optimization. However, existing algorithms for planning these activities and resources could not be directly applicable as either the algorithms do not address the specific characteristics of the problem or it contains certain limitations that need extensive investigation.

Food is one of the consequential entity in the entire food banking ecosystem. Most of the times the donated and then distributed food do not fulfill the dietary requirements of different section of beneficiaries because food banks distribute food without addressing the nutritional requirements of the end-beneficiaries. These requirements of dietary constituents vary depending upon gender and age group. Addressing the nutritional requirement based on age and gender profiling of end-beneficiaries could play a significant role in alleviating hunger and

malnutrition. Incorporating the nutritional aspect while planning for the food banks operations could lead to better utilization of food and meeting the dietary requirements of beneficiaries. These challenges were taken as motivation to start the study to navigate a path ahead in the direction of overcoming them.

1.6.Problem Statement

This research pertains to strategic, tactical and operational problem faced by food banks in Indian context. It addresses the key challenges existing in food banking system across globe as well as peculiar issues due to various intrinsic/regional characteristics of Indian food banks. During the research work, following expansive questions were identified and problem statement was developed -

- What are the barriers of food banks in Indian context?
- How these barriers are inhibiting the growth and expansion of Indian food banks?
- What is the cause-and-effect association of the barriers?
- How to ensure maximum collection and distribution of donated food and utilize scarce resources effectively?
- How to minimize the total transportation cost of food banks, ensure equitable distribution?
- How to implement and evaluate the algorithm to solve vehicle routing problem that can scale?
- How to plan for the network design of the Indian food banks and include nutritional aspect to it?

1.6.1. Research Problem 1

Food insecurity and wastage are critical global issues, particularly in developing countries like India, where millions suffer from hunger despite substantial food production. While food banks have been identified as a viable solution to mitigate hunger and reduce food waste, their adoption and effectiveness in India are significantly hindered by various barriers. These include logistical challenges, insufficient infrastructure, limited financial resources, and a lack of coordinated policy frameworks. Addressing these barriers is crucial for enhancing the efficiency and scalability of food banks, which are essential for achieving sustainable development goals related to hunger and food security. Failure to overcome these obstacles could result in continued food wastage and persistent hunger, undermining efforts to improve food security in India. This study aims to systematically identify, analyze, model and evaluate the barriers to the adoption and effective operation of food banks in India, with the goal of providing actionable insights and recommendations to enhance their integration within the country's existing ecosystem.

1.6.2. Research Problem 2

Efficiently managing the collection and distribution of food in food bank operations is a complex logistical challenge, particularly when vehicles must operate from multiple depots, adhere to strict time windows, and handle split pickups and deliveries. These operations are crucial for minimizing food waste, reducing costs, and ensuring that food reaches those in need. However, this specific scenario has been underexplored in existing research on vehicle routing problems. Inadequate solutions can lead to increased operational inefficiencies, higher food waste, and reduced service effectiveness. This research aims to develop and evaluate an efficient routing model and solution tailored to the unique logistical needs of food banks with

an ability to solve large scale instances contributing to more effective and sustainable food distribution practices. Moreover, it also aims to investigate and improve the existing state-of-the art algorithms proposed in the literature pertaining to multiple conflicting objectives for solving food banks distribution problem.

1.6.3. Research Problem 3

The design of an efficient network for Indian food banks is crucial to ensure the effective collection, storage, and distribution of food to vulnerable populations. The unstructured network of food banks with different mode of operation (front end – direct delivery to beneficiaries, back-end – delivery to other food banks and agencies) makes the problem even more complex. However, current network designs often overlook the critical aspect of nutritional quality and different mode of operation focusing primarily on logistical efficiency and food quantity. In a country like India, where malnutrition and hunger are prevalent, it is essential that food banks not only provide sufficient quantities of food but also deliver nutritionally balanced meals that meet the dietary needs of beneficiaries.

The challenge lies in developing a network design for Indian food banks that integrates logistical considerations, nutritional standards and modus operandi. This requires a comprehensive approach that addresses the complexities of food collection from diverse sources, storage, and distribution across vast geographic areas, all while ensuring that the food delivered meets essential nutritional criteria.

This research seeks to explore how to optimally design such a network for Indian food banks, incorporating nutritional aspects and hierarchies into the planning process to enhance the overall impact on food security and public health. The study will focus on creating a model

that balances efficiency with nutritional adequacy, aiming to improve the quality of food aid delivered to those in need across India.

In order to address the above research question, there is a requirement of a system that can perform the following task –

- Identify the critical barriers and evaluate its impact on the system.
- Aids, automate and improve the visibility of the daily operational problem of food banks.
- Improve the existing state-of-the-art algorithms that can undertake multiple conflicting objectives to solve the daily operational problem of food banks.
- Ensure maximum collection and distribution of donated food, effective utilization of scarce resources.

In alignment with the research questions mentioned in the above paragraphs, this research endeavors the following set of key objectives to address the problem. The five key objectives are enlisted as:

- To study the existing body of literature for food banks, to identify, model and evaluate its potential barriers.
- To propose a model and solution strategy for solving the daily collection and distribution problem of food banks.
- To investigate and improve the existing state-of-the art algorithms proposed in the literature pertaining to multiple conflicting objectives for solving food banks operational problem.
- To propose an efficient algorithm that can solve large scale instances.

- To design, analyze and study a supply chain network design model for Indian food bank incorporating the nutritional aspect of food in the system.

1.7. Research Contributions

1.7.1. Contributions to Research Problem 1

- We tried to identify the challenges that are hindering the growth of food banks by literature surveys and performing qualitative interviews of experts from academia and executives of some major food banks.
- We identified the critical barriers to the adoption and growth of food banks in India by performing interviews and brainstorming sessions.
- We evaluate barriers using the DEMATEL (Decision-Making Trial and Evaluation Laboratory) methodology. This method prioritizes barriers and establishes cause and effect relationship among the barriers for the adoption and growth of food banks in India.
- We further use the DEMATEL-based Analytic Network Process (ANP) (Tang, 2018) methodology to model this complex system by formulating a network of inter-relationships among the identified critical barriers. This is a unique approach to identify food bank barriers.

1.7.2. Contributions to Research problem 2

- In order to tackle the daily operational problem of collection and distribution, our work proposed a rich variant of Vehicle Routing Problem (VRP). Our study contributes to the body of literature of VRP as well as Food banks.

- We have included several realistic intricacies while solving for the routing problem such as allowing multiple visits to donors and beneficiaries to satisfy maximum demand and reduce food wastage, time windows within which food should be distributed to avoid perishability. To the best of our knowledge, these types of real case scenarios have not been explored.
- We proposed two variants of metaheuristic based on Genetic Algorithm (GA) to solve the proposed problem under several layers of complexity.
- The proposed algorithm outperforms the state-of-the-art solver Gurobi on two key performance indicators – efficiency and solution quality on the benchmark instances of VRP.
- We presented a case study on Robin Hood Army and proposed to minimize their total routing cost as well as tried to minimize the number of vehicles needed to perform that activity.
- Food banks strive to achieve the social objectives. Equity is one such goal, we endeavored it in Multi-Objective (MO) scenario. Precisely, we proposed a MO model having three trade-off objectives – cost, equity and shortage.
- We proposed a modified NSGA-II (Non-dominated Sorting Genetic Algorithm) to solve the MO model.
- The proposed model and algorithm is tested and validated on a case problem on an Indian food banks and produces efficient and near-optimal solutions.

1.7.3. Contributions to Research Problem 3

- We introduce mixed-integer programming model to design an integrated network that connects donors, food banks, and class of beneficiaries with distinct nutritional requirements.
- Our model accounts for periodic bulk donations of long-shelf-life foods from institutional donors and daily donations of excess short-shelf-life (cooked) food from small-scale donors. This dual approach targets both food insecurity and food waste.
- The model also incorporates the conversion of various donated food types, each with different nutritional values, into specific food packets. These packets are designed to meet the diverse nutritional needs of beneficiaries, taking into account their age groups and varied socio-economic vulnerabilities.
- Our model ensures nutritional requirements of beneficiaries of different types. This aspect related to food bank supply chain have been under explored in the literature.
- Numerical analyses conducted on a case study set in the Delhi-National Capital Region (NCR) of India reveal valuable insights that can assist decision-makers in integrated and centralized food banking ecosystem.

1.8. Thesis Outline

This section will give a brief detail about the overall organization of the thesis. Chapter 1 presents the introduction section which aims to define and describe the problem associated with food banks. Moreover, it conceptualizes the existing challenges and highlights the

motivation for undertaking the current study. It presents the research problem and key research objectives of this work.

Chapter 2 presents an in-depth literature review on the various challenges documented in the literature for food banks. It also presents the in-depth literature review on the characteristics of operational and strategic problem of food banks with an aim to identify the potential gaps associated within its body of literature.

Chapter 3 presents the identified barriers to the growth and adoption of food banks retrieved from literature review and expert opinion. It proposes the hybrid DEMATEL based ANP method for prioritization and classification of identified barriers into cause-and-effect group considering the underlying interdependence. It also presents key set of managerial insights to foster the growth of food banks based on the result produced. Part of the content of Chapter 3 has been published by Dubey and Tanksale, (2022).

Chapter 4 comprises of two sections based on single and multi-objective framework. The first sections address the daily operational problem of food banks as a rich variant of VRP considering the underlying realistic problem intricacies with an aim to minimize the total cost and formulates it as a mixed-integer problem. The mixed-integer problem is solved using Gurobi and to ensure the scalability hybridized Genetic Algorithms (GA) with local search techniques have been proposed. The second section solves the problem considering multiple conflicting economic and social objectives of food banks. The exact methods have been used to solve the problem on Gurobi and NSGA-II is proposed to solve the larger instances of the problem efficiently. Each of the section presents case-study on Indian food bank utilizing the real data obtained from Robin Hood Army, Lucknow to assess the applicability and performance of proposed algorithms. Part of the content of first section of Chapter 4 has been

published (Dubey & Tanksale, 2023a). Part of the content of second section of Chapter 4 has been published (Dubey & Tanksale, 2023b).

Chapter 5 presents the integrated food bank network design model considering the nutritional requirements of the beneficiaries based on their age and gender profile. It presents a base model with an objective for minimizing the shortage of demand under given set of capacity and resource constraint. It presents a bird-eye view on the impacts by providing 10 different variations of the base model to incorporate different objectives and requirements. It presents a real data-based case study to design a food bank network model in Delhi, capital of India. It presents detailed analysis and generate interesting insights for stakeholders. Part of the content of Chapter 5 has been published (Tanksale et al., 2024).

Chapter 6 finally concludes the work done in the thesis. It presents the limitations of current work and provides future research direction.