Integrating Metro Infrastructure in Circular Food Supply Chains: A Model for Decentralized Quito's Food Bank Network Redesign

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Abstract. Food waste and food insecurity are pressing global challenges. This study presents a novel approach to optimizing the food bank network redesign (FBNR) by leveraging the Quito Metro system to create a decentralized food bank network. We propose positioning lockers at metro stations for convenient food donations, which are then transported using the metro's spare capacity to designated stations for collection by charities. A blockchain-based traceability system with smart contracts serves as the core data management system, ensuring secure and transparent traceability of donations. Additionally, we develop a multi-objective optimization model aiming to minimize food waste, reduce transportation costs, and increase the social impact of food distribution. A mixed-integer linear programming (MIP) model further optimizes the allocation of donations to ensure efficient distribution. By integrating these models with the blockchain system, we offer a comprehensive solution to the FBNR, promoting a more sustainable and equitable food system.

Keywords: Multi-criteria Decision Making in Smart Transportation Systems · smart logistics · Integrated Passenger Freight Transportation · Blockchain · Food banks

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1 Introduction

Food waste and food insecurity are global challenges that necessitate innovative and effective solutions. Each year, a substantial amount of food is lost or wasted throughout the supply chain, contributing to hunger, malnutrition, and environmental degradation [1]. Food banks play a crucial role in mitigating these issues by rescuing and redistributing surplus food to those in need [2,3].

Traditionally, food banks operate within centralized networks where recovered food is stored and distributed from central locations. The supply chain operates with products being transferred by both donors and the food bank itself. The distribution of these products is then handled internally using the food bank's dedicated fleet of vehicles; however, this model often leads to logistical inefficiencies, limited reach, and accessibility issues, particularly in large urban areas. Studies highlight the need for improved logistics, transportation, and real-time tracking to mitigate food waste and enhance crisis preparedness [4–6]. To increase efficiency and expand the reach of food banks, it is essential to explore decentralized approaches that leverage existing and accessible infrastructure such as public transportation networks.

Recent research has increasingly focused on integrated passenger-freight transportation models, which leverage the unused capacity of public transportation to reduce urban congestion and improve efficiency [7]. These models, primarily studied in Europe and Asia, often focus on buses, metros, and trains as transportation modes, and shared vehicles as the most prevalent integration type. Given these advancements in transportation models, there is potential to apply similar strategies to improve food bank operations in urban environments.

Quito, the capital of Ecuador, faces significant socioeconomic challenges, with nearly 30 % of its 2.7 million residents living in poverty, experiencing high rates of underemployment and chronic malnutrition. This study focuses on the Quito Food Bank (QFB), a non-profit, which aims to combat hunger and reduce food waste by collecting surplus food from various sources and redistributing it to vulnerable population. Currently, the food bank operates a centralized distribution model. Given these inequitable conditions, optimizing food distribution is vital to ensure that marginalized groups receive adequate support.

The Food Bank Network Redesign (FBNR) problem can be optimized by leveraging the Quito Metro system, which commenced operations in December 2022, to create a decentralized food bank network. The proposed model involves installing food donation lockers at metro stations for convenient drop-offs, using the metro's spare capacity to transport food to designated stations for collection by charities. To enhance logistics and transparency, a blockchain-based traceability system is implemented, improving data flow and coordination among stakeholders.

The linear sequence of stations, including key sites that serve as collection points, facilitates efficient distribution and improves accessibility to impoverished areas. Furthermore, businesses in the Hotels, Restaurants, and Cafes (HORECA) sector near metro stations are identified as potential donors, strengthening the food bank's capacity to serve those in need. The diverse objectives of stakeholders must be considered to minimize food waste, reduce transportation costs, and enhance the social impact of food distribution, ultimately contributing to a more sustainable and equitable food system. The FBNR provides not only a potential solution for Quito but also a scalable framework that can be replicated in other metropolitan areas facing similar challenges.

2 Related Work

Addressing food waste and food insecurity through innovative strategies has garnered significant attention in recent years. Several studies have explored various aspects of food bank operations, optimization of food distribution, and the use of public transportation networks in logistics. Food waste is a critical issue with far-reaching implications for both the environment and society. Globally, an alarming one-third of food intended for human consumption is lost or wasted [8]. This not only represents a substantial economic loss but also contributes to environmental degradation and greenhouse gas emissions. As noted in [9], reducing food waste is crucial for enhanced food security and sustainability. They argue that effective food rescue and redistribution systems can play a pivotal role in achieving these goals.

The critical role of food banks in mitigating food waste and addressing food insecurity has been well-documented. In research by Davis et al. [10], they emphasize the importance of optimizing food bank operations to maximize their impact. The authors suggest that the efficiency of food banks can be significantly improved through better logistics and supply chain management practices. Similarly, [11] discuss the challenges faced by food banks, including the need for adequate infrastructure and resources to handle large volumes of food donations. Utilizing public transportation networks offers a novel approach to enhance food bank logistics.

Marinov et al. [12] highlight the benefits of using public transportation for urban freight, particularly in reducing traffic congestion and emissions. Likewise, Behiri et al. [13] demonstrate the potential for public transport to improve the efficiency and sustainability of urban logistics. Research shows that decentralizing food manufacturing and distribution can enhance resilience and flexibility during disruptions [14]. Integrating public transportation into this decentralized model further supports resilience by providing a reliable logistics framework.

Optimization models are widely used to address challenges in food distribution and supply chain management. Laporte et al. [15] provide a comprehensive overview of optimization techniques relevant to allocating food donations in this study. The effectiveness of MIP models in minimizing costs and improving service levels is explored by [16]. Several studies on food bank network redesign propose innovative approaches to improve food distribution efficiency and effectiveness. Beheshtian et al. [17] present a MO optimization model for designing food bank networks, focusing on transportation costs, food quality, and service coverage. The findings underscore the importance of balancing multiple objectives to achieve optimal solutions in complex logistical networks.

The redesign of a multi-echelon food bank network for collecting and distributing donations has been discussed [18]. Strategic decisions included opening new food banks, determining storage and transport capacities, and potentially closing or expanding existing ones. They proposed a MIP model that integrates economic, environmental, and social sustainability objectives, validated through a computational study on the Portuguese Federation of Food Banks network. [19] introduced three decompose-and-fix heuristics for the multi-period, multi-product FBNR, focusing on several objectives. Each heuristic simplifies the problem by breaking it into two Multi-Objective Mixed Integer Programming (MO-MIP) problems, significantly reducing computation time. These heuristics reduce Central Processing Unit (CPU) time by 80 % to 97 % compared to exact methods and can be adapted for other large MO problems.

Reusken et al. [20] presented an optimization model designed to allocate investment budgets to increase the number of beneficiaries served by food banks. They prioritize investments with the largest social impact and account for real-world challenges like decentralized organizations, data limitations, and varying transport and storage capacities. The Dutch Food Banks Association has applied these findings in practice, recommending targeted investments that could increase capacity and serve approximately 32 % more beneficiaries.

Suarez et al. [21] propose a novel multi-objective, multi-product, and multi-period model to address the challenge of allocating perishable food items in food bank warehouses. The model aims to ensure food safety, meet nutritional needs, and minimize shortages while adhering to a first expired-first out policy. The effectiveness of the model is demonstrated using real-world data from the Diakonia Food Bank in Guayaquil-Ecuador. Optimization models are critically dependent on the accuracy and reliability of their underlying data management systems. As food bank networks increase in complexity and scale, conventional data management approaches may prove insufficient in providing the necessary monitoring across decentralized networks.

Blockchain systems, such as those outlined by Musamih et al. [22] and IBM Food Trust [23], offer a decentralized and tamper-resistant ledger that significantly enhances data transparency and traceability within supply chains. These systems can leverage smart contracts to automate regulatory compliance and maintain data integrity. Such frameworks can be adapted to address the specific needs of food bank networks. When integrated with public transportation systems, blockchain technology can complement robust optimization models to foster more efficient and resilient food bank operations.

3 Information Management in Food Bank Logistics

Conventional approaches to food bank supply chain traceability are often centralized and opaque, despite growing demand for greater transparency from consumers and stakeholders [24]. The sector's unique characteristics and the integration of multiple stakeholders, from donors to beneficiaries, amplify these challenges. Adopting digital technologies, such as blockchain, can further enhance traceability and transparency [25].

Blockchain is particularly well-suited for traceability in a decentralized food bank network due to its inherent characteristics that align with the needs of such system, improving decision making and operational efficiency. Central to this approach is the concept of a Traceable Resource Unit (TRU) [26], which is key for tracking a food item's journey from donation to distribution, ensuring comprehensive transaction history and real-time monitoring. In the proposed FBNR model, donors pack food in uniquely identifiable *boxes*, that serve as TRUs, which balance detailed tracking with efficient management across the blockchain.

3.1 Blockchain-Enhanced Traceability in FBNR

The proposed system utilizes blockchain technology to improve traceability within the food bank supply chain. By employing a smart contract (SC), stakeholders interact securely and transparently, enabling real-time tracking, maintaining data integrity, and ensuring transparent transactions through decentralized storage. A SC is a self-executing agreement where the terms are encoded directly written into lines of code, this provides an immutable and decentralized environment, enhancing trust and regulatory compliance, which in turn improves the overall reliability of the supply chain.

A high-level system architecture of the proposed food bank traceability system includes stakeholders and their interactions with the SC (see Fig. 1). Stakeholders will use software devices to interact with the SC and other resources through a user interface layer provided by a Decentralized Application (DApp). This DApp connects to the SC and storage systems via application programming interfaces (APIs). Stakeholders will be able to execute and access authorized functions, data files from decentralized storage, Interplanetary File System (IPFS) hashes, and transaction details from on-chain resources.

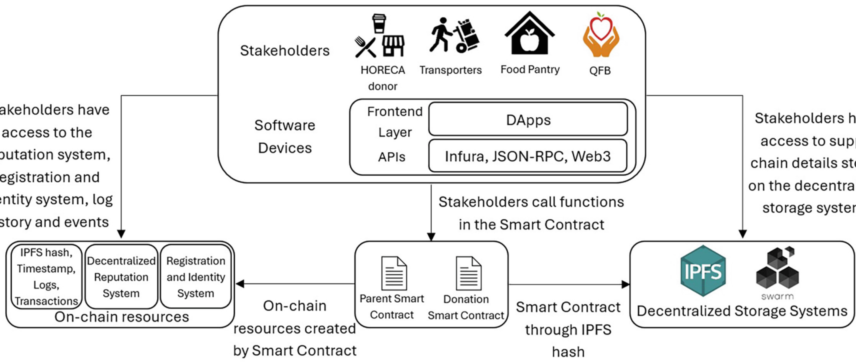


Fig. 1. High-level system architecture for the food bank blockchain-based solution

An event in this context is a distinct action or occurrence within the supply chain that triggers the execution of predefined functions within the SC. Each stakeholder in the supply chain is assigned specific roles and permissions within the SC, ensuring transparency and accountability throughout the process. The SC records every transaction and status update related to the donations, providing real-time traceability to all participants. Each transaction is authenticated, verifiable, and safely logged, further ensuring the integrity and reliability of the system. Details of the donation or other identification techniques such as the images, can be uploaded to IPFS, which will then provide a hash to the SC during each event. The Supply Chain events are as follows:

- *Donation Initiation:* The HORECA donor will request the initiation of the donation process to QFB. Once the request is approved, an event is triggered. The donor will pack the food, drop it off at the metro station locker.
- *Distribution:* The donation is transported via the metro system and the QFB vehicle fleet. Volunteers facilitate the loading of donations from lockers to metro wagons and unloading at destination station from metro wagons to QFB vehicles. The details of the package will be updated at loading and unloading points.
- *Classification and Final Distribution:* Upon arrival at the collection centers, donations are classified. Depending on the classification, donations are either distributed to beneficiaries or sent to composting facilities. Every action is logged, forming a sequence of events, ensuring traceability from donation initiation to final distribution.

3.2 Implementation of Proposed Traceability System

The donor will deploy a SC defining the details of the food donation lot, triggering an event to notify all supply chain participants. New participants can access these events and track the donation's history since the information is stored permanently on the ledger. The donor may also upload an image of the lot to IPFS for visual inspection by participants. The donor will package the lot, drop it off at a secure locker, and announce its availability for transfer via an event. Transporters interested in transferring the lot in the loading and unloading points will use a specialized function. At each step of the transfer, an event will notify participants of the new owner. The approval for the SC deployment is not considered for simplicity.

An Entity-Relationship diagram (see Fig. 2) illustrates the key entities and how they interact with the SC. It considers attributes like *ownerID*, which stores the blockchain address of the current contract owner. The Donation Lot SC can have only one owner at a time. When ownership changes, an event is triggered and recorded on the blockchain, enabling the tracing of the donation lot's origin.

Since the SC represents a specific donation lot, it includes additional attributes like *donationID*, *lockerID*, *numBoxes*, *image*, and *metroWagonID*. There are also five mappings for the authorized entities: donors, transporters,

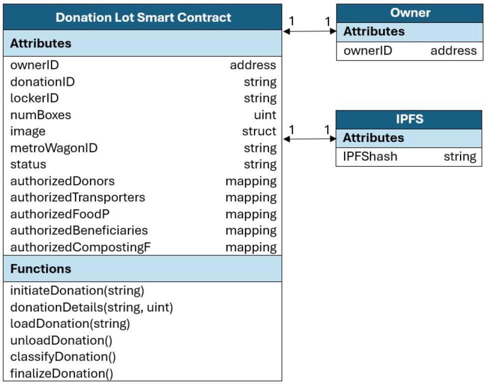


Fig. 2. Entity-Relationship Diagram for Donation Lot Smart Contract

food pantries, beneficiaries, and composting facilities, who have access to certain functions within the contract. Several functions are included to manage the donation process. Donation details, including *donationID* and *numBoxes*, are added through the *donationDetails* function. The SC and IPFS relationship is 1:1, as each donation lot will have one image uploaded to IPFS.

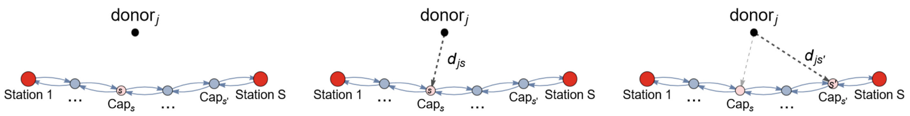
Each HORECA donor declares to participants that the donation lot is available for pick up in the locker via the *initiateDonation* function with *lockerID* as a parameter. An authorized entity intending to load the lot onto the metro wagon invokes the *loadDonation* function, inputting the *metroWagonID*, which subsequently updates the ownership to the designated transporter. Similarly, an entity interested in unloading the lot from the metro wagon executes the *unloadDonation* function, updating the ownership to the food pantry. The pantry then classifies the boxes suitable for consumption, executes the *classifyDonation* which updates the ownership to the composting facilities for the not suitable boxes. The final distribution to the beneficiary is executed with the *finalizeDonation* function, setting the beneficiary as the ultimate owner.

4 Optimization Models for Efficient Donation Distribution

This section delves into the optimization of the donation distribution chain, employing two distinct mathematical models. The first model focuses on the strategic assignment of donors to specific metro stations, aiming to minimize transportation distances and ensure efficient utilization of station capacities. The second model tackles the operational challenge of optimizing the transportation of donations on metro trains, considering factors such as train schedules, loading/unloading times, and storage costs. Both models are designed to address the diverse and sometimes conflicting interests of various stakeholders, including donors, passengers, transportation authorities, and the food bank itself.

4.1 Assignment Model

This model aims to assign donors to the nearest metro station with sufficient capacity to receive their donations, thus minimizing overall travel distance. Station capacity is defined as its ability to handle cargo without impacting passenger service. In scenarios where station i is closest to donor j and possesses the capacity to accommodate the donor's load, this station is designated as the optimal drop-off point (see Fig. 3a and Fig. 3b). However, if station i lacks the necessary capacity, the model dynamically selects the nearest station that can fulfill the capacity requirement (see Fig. 3c).



(a) donor location (b) station assignment (c) alternative station

Fig. 3. A Donor-Station Allocation Model

Considering the aforementioned factors, a straightforward allocation model incorporating capacity constraints is employed. This leads to the formulation of a MIP model, where the specific elements are detailed in Table 1.

Table 1. Assignment Model

Type	Description
Sets	
$j : 1, ..., J$	Donors
$s : 1, ..., S$	Stations
Parameters	
Cap_s	Donation load capacity at station s
O_j	Donor j's offer
$d_{j,s}$	Unit cost of shipping each unit of donations from donor j to station s
Decision Variables	
$x_{j,s}$	1 If donor j's offer is assigned to station s, 0 otherwise

The model can be formulated as:

$$Min\ Z = \sum_{j=1}^{J} \sum_{s=1}^{S} d_{js} O_j x_{js} \tag{1}$$

subject to:

$$\sum_{j=1}^{J} x_{j,s} O_j \leq \ Cap_s, \quad s = 1,\ 2, \ldots,\ S \tag{2}$$

$$x_{j,s} \geq \ 0 \ s = 1,\ 2, \ldots,\ S, j = 1,\ 2, \ldots,\ J \tag{3}$$

4.2 Storage and Distribution Model

The second model optimizes the food donations transportation from donors to the Metro system's stations, ultimately destined for the food bank's two food pantries at the network's northern and southern ends, as show in Fig. 4. The model considers the loading station ls_i for each donation i, the designated unloading station us_i, and the transportation time ts_s between station s and the next station. The food donations are packaged into standardized boxes as TRUs by the respective donors. The boxes are temporarily stored incurring a storage cost at their assigned stations. Subsequently, these boxes are loaded onto *caddies*, wheeled devices for conveying multiple boxes, and transported via the metro system to their designated destination stations. Upon arrival, each donation is retrieved from the caddies and then transferred to the final food pantry as shown in the Fig. 6.

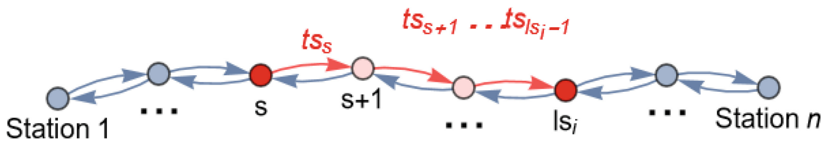


Fig. 4. Schematic Representation of the Donor Load Transportation Model 2

Given these considerations, we formulate the MO optimization model (4)–(22) whose sets, parameters, and decision variables are detailed in Table 2.

$$min \ (Z_1, Z_2, Z_3) \in \mathbb{R}^3 \tag{4}$$

where:

$$Z_1 = \sum_{i=1}^{I} \sum_{j=1}^{J} (G_i - g_i \ x_{i,j,ls_i}) \tag{5}$$

$$Z_2 = \sum_{s=1}^{S} \sum_{i \in II_s} \sum_{j=1}^{J} h_j \ B_i \ x_{i,j,s} \tag{6}$$

$$Z_3 = \ \sum_{i=1}^{I} P_1 B_i \left(G_i - g_i \ \right) + \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{j \in F_f} P_{2,j} B_i \left(E_i - \sum_{s \in I_s} ts_s \ \right) \tag{7}$$

The objective functions, represented by Eqs. (5), (6), and (7), aim to:

– Minimize Z_1, the total time that donations remain at stations awaiting loading (5).

Table 2. Storage and Distribution Model

Type	Description
Sets	
$i : 1, \ldots, I$	Set of donations
$j : 1, \ldots, J$	Set of trains
$s : 1, \ldots, S$	Set of stations
$f : 1, \ldots, F$	Set of transportation fares
Parameters	
g_i	Time at which donation i is available for transport
ls_i	Departure station for donation i
us_i	Unload station for donation i
P_1	Unit cost of storing a box per time unit at a station
$P_{2,j}$	Unit cost involved in sending a box on train j (\$/box)
F_f	Trains subject to fare f
l_j	Train j's departure time from station 1
ST_s	Storage capacity at station s (boxes)
ts_s	Travel time between station s to the adjacent station
I_s	Set of donations needing to pass by station s on their way
II_s	Set of donations arriving at station s; $s = 1$ or $s = S$
D_i	Set of donations departing from the same station as donation i and ready for departure earlier than i: $D_i = \{k \mid g_k \leq g_i \wedge ls_k = ls_i\}$
V_i	Volume of donation i
W_i	Weight of donation i
BVC	Maximum volume capacity of boxes
BWC	Maximum weight capacity of boxes
B_i	Number of boxes required for donation i
Q_j	Train j 's box transport capacity
WT_{max}	Maximum train dwell time at any station s
WT_{min}	Minimum train dwell time at any station s
h_j	Time required to handle (load/unload) one box on train j
M	Sufficiently large number
Decision Variables	
$x_{i,j,s}$	1 if donation i is in train j at station s, 0 otherwise
$u_{k,i}$	1 if k is in D_i and k is not yet loaded when i becomes ready for departure
$C_{j,s}$	Waiting time of train j at station s
G_i	Time at which donation i is loaded (at station ls_i)
E_i	Time at which donation i arrives at its destination station 1 or S

– Minimize Z_2, the total time spent on loading, unloading, and transporting the boxes (6). Note that the in-transit time for boxes is constant regardless of train assignment; thus, only loading and unloading times vary based on the chosen schedule.
– Minimize Z_3, the combined transportation and storage costs from donation arrival at departure stations to delivery at destination stations (7).

Subject to constraints (8)–(22). i.e., subject to:

$$\sum_{j=1}^{J} x_{i,j,ls_i} = 1, \quad i = 1,\ 2, \ldots,\ I \tag{8}$$

Equation (8) ensures that each donation is assigned to a single train for transportation, and this assignment occurs precisely once.

$$x_{i,j,s} - x_{i,j,s+1} = 0, \quad \forall\ s \in \left[ls_i, us_j - 1\right], i = 1,\ 2, \ldots,\ I \tag{9}$$

(9) ensures that once a donation is assigned to a train, it passes through all intermediate stations between its departure and arrival points.

$$\sum_{i \in I_s}^{J} x_{i,j,s}\ B_i \le Q_j, \quad j = 1, \ldots, J,\ s = 1, \ldots, S \tag{10}$$

(10) guarantees that a donation can only be allocated to a metro vehicle that reaches its origin station after the donation's ready time.

$$x_{i,j,ls_i}\ g_i \le\ l_j + \sum_{s=1}^{ls_{i-1}} \left(C_{j,s} + ts_s\right), \quad i = 1, \ldots, I,\ j = 1, \ldots, J \tag{11}$$

(11) guarantees that a donation can only be assigned to a metro vehicle that reaches its destination station after departing its origin station.

$$C_{j,s} \ge\ WT_{min}, \quad j = 1, \ldots, J,\ s = 1, \ldots, S \tag{12}$$

$$C_{j,s} \le\ WT_{max}, \quad j = 1, \ldots, J,\ s = 1, \ldots, S \tag{13}$$

(12) and (13) guarantee that the waiting time at each station adheres to the specified minimum and maximum limits.

$$C_{j,s} \ge \sum_{i \in II_s} h_j\ x_{i,j,s}\ B_i, \quad j = 1, \ldots, J,\ s = 1, \ldots, S \tag{14}$$

(14) ensures that the waiting time of each train at each station falls within the feasible range.

$$B_i = Max \left\{ \left\lceil \frac{V_i}{BVC} \right\rceil, \left\lceil \frac{W_i}{BWC} \right\rceil \right\} i = 1, \ldots, I \tag{15}$$

Equation (15) is designed to quantify the number of boxes required to pack each donation.

$$G_i \geq \ l_j + \sum_{s=1}^{ls_{i-1}} (C_{j,s} + ts_s) - M(1 - x_{i,j,ls_i}), \ \ i = 1, \ldots, I, \ j = 1, \ldots, J \quad (16)$$

(16) establishes the earliest feasible time at which each donation can be loaded onto a train.

$$G_k \leq \ g_i + M \ u_{k,i}, \ k \in \ D_i, \ i = 1, \ldots, I \quad (17)$$

(17) ensures the logical consistency of variables $u_{k,i}$.

$$\sum_{k \in D_i}^{J} u_{k,i} \ B_k \leq ST_{ls_i} - B_i, \ i = 1, \ldots, I \quad (18)$$

(18) enforces the storage capacity limit at each station.

$$x_{i,j,s} \in \{0,1\}, i = 1, \ldots, I, \ j = 1, \ldots, J, \ s = 1, \ldots, S \quad (19)$$

$$C_{j,s} \geq 0, \ j = 1, \ldots, J, \ s = 1, \ldots, S \quad (20)$$

$$G_i \geq 0, i = 1, \ldots, I \quad (21)$$

$$u_{k,i} \in \{0,1\}, \ k \in \ D_i, i = 1, \ldots, I \quad (22)$$

(19) to (22) serves to define the nature of the decision variables within the model. It establishes that $x_{i,j,s}$ and $u_{k,i}$ are binary variables. Furthermore, it designates G_i and $C_{j,s}$ as non-negative real variables.

One way to solve the proposed MO model is through the standardization of z_1, z_2 and z_3, so that all objectives are on the same scale and comparable, and then transforming them into a single objective function through a weighted sum of those objectives, as established in [27]. Standardization is achieved by transforming the values of each objective function Z_i into values within the interval $[0,1]$, for which the largest, Z_i^U, and lowest, Z_i^L, values that Z_i, $i =$1,2,3 can achieve, are calculated by transforming the MO model represented in Eq. (4) into a weighted single-objective represented in Eq. (23).

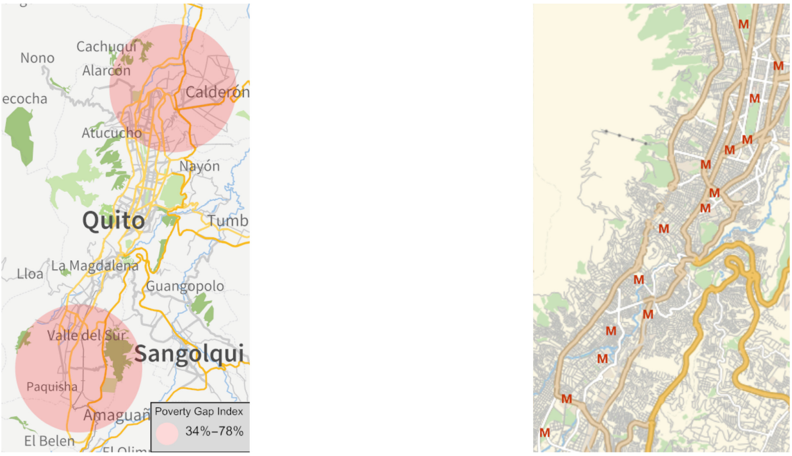
$$\min \alpha_1 \frac{(Z_1 - Z_1^L)}{(Z_1^U - Z_1^L)} + \alpha_2 \frac{(Z_2 - Z_2^L)}{(Z_2^U - Z_2^L)} + \alpha_3 \frac{(Z_3 - Z_3^L)}{(Z_3^U - Z_3^L)} \quad (23)$$

where the parameters α_i satisfy the conditions $\alpha_i \geq 0$ and $\sum_i \alpha_i = 1$. By systematically varying the values within the triplet $(\alpha_1, \alpha_2, \alpha_3)$, we can effectively approximate the Pareto front of the MO problem.

The proposed model, solvable using a MIP solver, generates a set of non-dominated solutions and an estimate Pareto front. These results empower food bank managers to assess the trade-offs between competing objectives and select the optimal donation distribution strategy that leverages the metro public transport network. This approach facilitates the minimization of distribution and storage costs while maintaining acceptable service levels for passengers.

5 Quito Metro Case Study: Findings and Insights

Quito, the capital of Ecuador, is nestled within the Andean mountain range. Its urban area is constrained by mountains and gorges to a long, narrow plateau. With a population of 2.7 million, representing 16 % of the national total, Quito faces significant socioeconomic challenges. Notably, nearly 30 % of its residents experience poverty, with 7 % living in extreme poverty and almost 30 % of children under five suffering from chronic malnutrition. Unemployment and under-employment rates stand at 5 % and 40 %, respectively, with poverty concentrated in the city's northern and southern extremities [28] (see Fig. 5a).



(a) Quito´s Poverty gap distribution (b) Metro of Quito line

Fig. 5. Mapping Poverty in Quito: A Comparison with Metro Line Coverage

The QFB is a non-profit organization dedicated to fighting hunger and reducing food waste in Quito, Ecuador. Founded in 2003, the bank collects surplus food from various donors, including hotels, restaurants, markets and food producers, and redistributes it to beneficiaries.

Currently, the food bank operates a centralized distribution model, with a central warehouse located in the south of the city. Food donations are collected by the bank's fleet of 3 vehicles and transported to the warehouse for sorting and storage. From there, food is distributed to beneficiary organizations.

The proposed decentralized model leverages the Quito Metro system to create a network of food donation lockers and collection points. Key elements include the installation of secure lockers at strategically chosen metro stations for convenient food donation drop-offs, the use of the spare capacity of metro trains to transport food donations to designated collection points, the development of a data traceability architecture to track and manage the flow of donations, and the implementation of MO-MIP programming models to optimize the allocation and distribution of donations.

This innovative approach is expected to increase the reach of the food bank by leveraging the extensive metro network, reducing transportation costs by decreasing dependency on the food bank's vehicle fleet, improving the efficiency of the logistics process by resulting in more efficient distribution, and enhancing social impact by increasing the volume of food rescued and redistributed, thus benefiting more individuals in need [14]. This supports the Food loss and waste (FLW) law's focus on prioritizing the responsible treatment of food fit for human consumption while also establishing a "culture of donation" [29].

The Quito Metro, an underground public transport network, commenced operations in December 2022. The fully operational line spans 23 km, and serves as the backbone of the Quito Integrated Mass Transportation System (SITM-Q) [30] (see Fig. 5b).

The linear structure of the Quito Metro's first line, featuring a series of stations arranged sequentially, aligns well with the integrated passenger-freight transportation model proposed in [31]. This model serves as a foundation for our proposed food bank supply network design, facilitating the efficient transportation of food to two strategically located food pantries at the northern and southern ends of the city. These nodes are in close proximity to the areas with the highest concentration of poverty, ensuring accessibility for those who would benefit most from the food bank's services.

Within this framework, Quitumbe station (station 1) and El Labrador station (station 15) function as unloading points for food collected at each of the "interior" stations (stations 2 to 14). These interior stations act as loading and unloading points, enabling donors to conveniently deposit food donations, which are then transported along the metro line to the food pantries. This integrated approach optimizes the utilization of existing infrastructure, reduces transportation costs, and streamlines the distribution of food. (see Fig. 6).

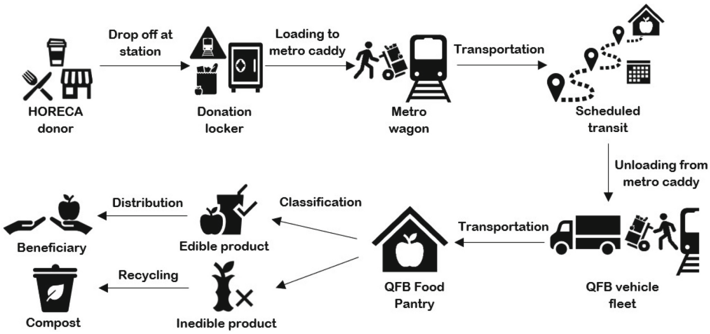
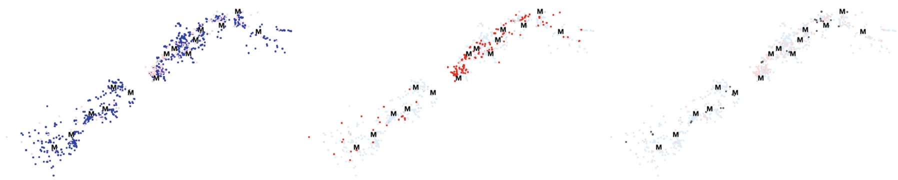


Fig. 6. FBNR Supply chain stakeholders and their relationships

In this study, businesses within the HORECA sector situated in proximity to the Quito Metro network are identified as potential donors. Given the nature of their products, these establishments are well-suited to contribute to the food bank, and their proximity to metro stations facilitates efficient distribution. The spatial distribution of 1,200 such establishments, categorized by type, is illustrated in Fig. 7.



(a) Restaurant locations (b) Hotel locations (c) Cafe locations

Fig. 7. Distribution of HORECA establishments near the Quito Metro, by type.

The visualization presented in Fig. 8 illustrates the outcome of the donor-station assignment process, wherein each potential donor within the HORECA sector is allocated to the most suitable metro station for their food donations.

Fig. 8. Spatial Allocation of Donors to Metro Stations in Quito

To showcase the model's real-world applicability, we utilized data from the QFB and potential food donations from HORECA establishments. The MIP model in Eq. (23) was implemented and solved using GAMS [32] for algebraic modeling and the Gurobi solver [33] for optimization. Gurobi's exact methods efficiently determined optimal solutions for various α_i weight combinations. Table 3 presents the values of objective functions z_1, z_2, and z_3 for different α_i combinations, along with their respective computation times. The results underscore the model's computational efficiency in handling real-world scenarios within reasonable time frames. Numerical results reveal conflicts among the considered objectives, highlighting the value of the Pareto front in providing decision-makers with valuable insights for further analysis and decision-making.

Table 3. Values of the objective functions for different combinations of α_i

(α_1, α_2, α_3)	Z_1	Z_2	Z_3	Execution time (sec)
(0, 0, 1)	1.175816	1.45778	0.250568	1.2562
(0, 0.5, 0.5)	1.385439	0.1023	1.709063	1.3231
(0.33, 0.33, 0.33)	0.93239	1.04235	1.693897	1.6598
(0, 1, 0)	1.211361	0.05842	0.918517	1.6924
(0.5, 0.5, 0)	1.94141	0.677836	0.10142	1.9335
(1, 0, 0)	0.31225	1.522893	1.23824	1.7226

6 Conclusions

This study proposes the integration of logistics models with public transportation systems to enhance food bank operations in urban environments. The utilization of the unused capacity of mass public transportation, exemplified by the Quito Metro system, represents a promising approach for optimizing food distribution. However, practical implementation of such systems remains limited in Latin America, including Ecuador.

The proposed information management system incorporates blockchain technology to enhance traceability within the food bank supply chain. By defining clear relationships among stakeholders, on-chain resources, and decentralized storage systems, the system facilitates real-time monitoring of donations through unique smart contracts. These contracts trigger events upon ownership changes, with event data accessible to DApp users. This approach aims to improve transparency, reduce human intervention, and minimize delays, by integrating seamless collection, organization, presentation, and utilization of logistics data.

Several limitations are acknowledged, including constraints related to modeling and network topology. The focus on a linear metro structure, rather than more complex configurations with multiple lines and interchanges, restricts the generalizability of the findings. Furthermore, the smart contract was neither implemented nor tested, which limits the ability to assess its practical effectiveness. Future research should address these limitations by exploring more intricate network topologies while conducting security and cost analyses of the proposed blockchain-based solution.

Further investigation is required into the technical infrastructure necessary to support the model, including the design of TRUs, secure lockers and modified subway cars. The operations management associated with the creation and utilization of standardized boxes warrants additional attention. Standardized boxes could enhance automation, sorting, data management, transportation, and regulatory compliance in the food bank network through consistent labeling, uniform dimensions, and simplified inventory management.

Refining these components is essential to optimizing the transportation within the food bank network. Future work should address the design and functionality of these elements to better support the logistics of the food distribution system. Additionally, a comprehensive analysis of the economic, legal, social, and psychological implications of the model is still needed.

Finally, the model must also account for the stochastic nature of the system, including variability in donation volumes and potential delays in transportation. Addressing these unpredictable factors is essential for enhancing the efficiency and effectiveness of the food distribution network.

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