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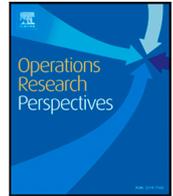
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Multi-objective optimization for perishable product dispatch in a FEFO system for a food bank single warehouse

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ABSTRACT

One of the main challenges of food bank warehouses in developing countries is to determine how to allocate perishable products to beneficiary agencies with different expiry dates while ensuring food safety, meeting nutritional requirements, and minimizing the shortage. The contribution of this research is to introduce a new multi-objective, multi-product, and multi-period perishable food allocation problem based on a single warehouse management system for a First Expired-First Out (FEFO) policy. Moreover, it incorporates the temporal aspect, guaranteeing the dispatch of only those perishable products that meet the prescribed minimum quality standards. A weighted sum approach converts the multi-objective problem of minimizing a vector of objective functions into a scalar problem by constructing a weighted sum of all the objectives. The problem can then be solved using a standard constrained optimization procedure. The proposed mixed integer linear model is solved by using the CPLEX solver. The solution obtained from the multi-objective problem allows us to identify days and products experiencing shortages. In such cases, when there is insufficient available inventory, the total quantity of product to be dispatched is redistributed among beneficiaries according to a pre-established prioritization. These redistributions are formulated as integer programming problems using a score-based criterion and solved by an exact method based on dynamic programming. Computational results demonstrate the applicability of the novel model for perishable items to a real-world study case.

1. Introduction

Food banks play a crucial role in addressing food insecurity and hunger. Riches (1986) [1] delineated them as “centralized warehouses or registered clearinghouses, operating as nonprofit entities, with the primary objective of collecting, storing, and distributing surplus food (donated/shared) free of charge, either directly to individuals in need or to frontline social agencies providing supplementary food and meals”. Riches (2002) [2] also explains how a decrease in government welfare spending has turned food banks into “secondary extensions of weakened social safety nets”. Meanwhile, Cloke (2017) [3] characterizes food banks as “spaces of care” that provide essential emergency food aid, and Webb (2013) emphasizes their crucial function in bridging gaps left by government assistance programs. Despite being prevalent in developing nations, the issue of food insecurity persists in the United States and other industrialized countries as well (McIntyre

et al. 2016) [4]. Lambie-Mumford (2019) [5] frames food banks as emblematic of a broader political-economic shift in social policy.

The operational model of food banks involves the collection of donations and the distribution of groceries to those in need. However, Bazerghi's (2015) [6] comprehensive review underscores the inherent limitation of food banks in providing an adequate supply of nutritious, perishable foods. Their heavy reliance on donated and surplus food from retailers, producers, and the public exacerbates the challenge. Handforth's (2013) [7] findings indicate that most food banks distribute fresh produce and implement nutrition policies to minimize low-nutrient items. In contrast, Tarasuk (2005) [8] presents a conflicting perspective, contending that food banks' dependence on donated surplus food often results in the distribution of items unsuitable for meeting the specific dietary needs of individuals. Effectively addressing this operational challenge becomes more critical in the global context of

Abbreviations: FEFO, first expired-fist out; MILP, Mixed Integer Linear Programming

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poverty and extreme poverty, primarily impacting developing nations. In Latin America and the Caribbean, hunger prevalence reached 9.1% in 2018, the highest figure in 15 years, albeit slightly below the world average of 9.9%. It is concerning to note that, according to the 2022 report from the Food and Agriculture Organization of the United Nations (FAO) [9], regional hunger increased by 2% between 2019 and 2020. These statistics emphasize severe food insecurity in the region, demanding urgent attention and intervention. In Ecuador, the poverty rate reached 25% in 2021, with a troubling 7.9% of the population living in extreme poverty. Additionally, around 23% grapple with the pressing issue of food insecurity, resulting in a malnutrition prevalence of 7.9% (INEC, 2021). The intersection of these figures highlights the critical need to address the operational challenges of food banks to ensure the effective distribution of products that maintain their nutritional properties despite their perishable nature, especially in regions with high food vulnerability, as mentioned.

According to the Food and Agriculture Organization of the United Nations (FAO), Ecuador ranks second in South America for hunger prevalence, with about 15.4% of its 18 million citizens, approximately 2.7 million people, affected [9]. Food security becomes a privilege in developing countries like Ecuador, Arteaga (2022) [10]. Guayaquil, Ecuador's most densely populated city, grapples with significant economic vulnerability, marked by a complex interplay of poverty, social inequality, high crime rates, and substandard living conditions, highlighting the multifaceted nature of these pressing socioeconomic issues. Additionally, food security has emerged as a critical concern. Despite extensive efforts by organizations and food banks, challenges persist in reducing food waste and ensuring adequate donations. Data from the World Food Program (WFP) and the Guayaquil Food Bank underscore the urgency of addressing these issues, as many Ecuadorian households struggle to access essential food items while facing substantial food losses in the supply chain. Diakonia, located in Guayaquil, is the first fully established food bank in Ecuador, and it holds accreditation from the Global FoodBanking Network. It collaborates with 82 beneficiary organizations to reach over 30,000 individuals within its service area, approximately 80% of whom are children. Diakonia offers various programs, including a medicine bank, a fruit and vegetable rescue program, and the promotion of community gardens. Notably, 90% of the donated items consist of food, with the remaining 10% encompassing personal hygiene products, clothing, and medicines.

The utilization of optimization models in food bank product allocation and dispatch processes leads to a significant improvement in both the efficiency and quality of service delivery. These models promote a more equitable and efficient distribution of resources, with a direct positive impact on beneficiary satisfaction. Particularly, integer programming emerges as a vital tool in tackling the associated challenges, notably in the distribution of perishable goods. Through integer programming, food banks minimize waste and ensure product freshness. In addition, these models facilitate rapid adjustment to changing food availability and evolving nutritional beneficiary needs. The collective use of optimization models, with a particular focus on integer programming, significantly enhances food bank efficiency and effectiveness. Consequently, it leads to a marked improvement in the quality of life for vulnerable individuals.

This research focuses on developing a mixed-integer optimization model with multi-period and multi-product constraints, emphasizing a bi-objective function. The core objective is to determine the optimal scenario for meeting demand while efficiently managing uncertainties in distributing donations.

The rest of the paper is structured as follows. In the next Section, we review some related works to food bank operations. The motivation and contribution of this work are then presented in Section 3. The problem description and mathematical models are introduced and explained in Section 4. Real-world application is presented in Section 5. Finally, the conclusions and future research directions are discussed in Section 6.

2. Literature review

This Section categorizes previous optimization-based studies based on the following criteria: the uncertainty of the involved parameters, objective function components, constraints, product lifetime, solution methodology, nutritional approach, and warehouse management policies. Thus, we can place our work in the current literature and identify relevant research gaps.

One of the main features of food bank warehouses is how the available products are allocated to beneficiaries and how their magnitude is considered in the objective of the problems. Mohan et al. [11] report that in the United States, nonprofit food banks rely on donations from individuals, grocery stores, and organizations, and subject the food received to rigorous inspections to remove damaged or expired items. The study utilized a simulation model to enhance efficiency and improve food distribution, increasing food recipients and reducing food wastage. Orgut et al. [12] aimed to maximize the equitable distribution of food to various counties within a food bank's service area. Their focus was on minimizing the maximum absolute deviation from a perfectly equitable distribution, thereby improving the overall equity in the entire service region. Sazvar et al. [13] considered perishable products with specified expiry dates, where demand was deterministic but varied over time. The objective was to minimize the total cost, encompassing procurement, joint ordering, inventory holding, lost sales, and expiry costs, thereby optimizing the allocation of resources. Ortuno et al. [14] introduced a model for sending specific nutritional products to families, aiming to maximize the energy content (kilocalories) distributed to all served families in a day. Orgut et al. [15] addressed the uncertainty in food donations by maximizing the total amount of food shipped while minimizing the risk of food spoilage. This approach helps improve food bank operations and reduce waste. Fianu et al. [16] investigated different allocation rules and provided county-level estimates of unmet needs. Food donations were distributed based on county demand, available inventory, and predefined allocation rules, focusing on equity and effectiveness. Gomez et al. [17] introduced an objective function to maximize the collected scores from served beneficiaries, considering their priorities and needs. Castanon et al. [18] aimed to minimize costs associated with the weekly provision of nutritional resources to different beneficiary groups. The model considered factors such as the price per kg of food groups, the amount purchased, economic penalties for unmatched nutritional requirements, and unmatched nutrient quantities. Alkaabneh et al. [19] introduced binary decision variables to optimize food bundles' distribution over time, maximizing the expected utility of agencies over a finite horizon.

Hasnain et al. [20] developed a multi-criteria optimization model considering equity, effectiveness, and efficiency. To balance these criteria, the objective function incorporated weighted deviations from perfect equity, effectiveness, and efficiency. Ma et al. [21] characterized an optimal allocation policy as a two-threshold policy, considering both fairness and efficiency. Their objective function combined fairness and efficiency measures, creating a dynamic programming model for sequential resource allocation. Firouz et al. [22] incorporated a penalty factor in the objective function to simultaneously account for efficiency and equity. Their model sought to maximize fill rates across the network while penalizing deviations from maximum fill rates to balance efficiency and equity. Another challenge for food banks is effectively managing their product inventory for distribution to beneficiary agencies. Food banks function as central nodes that consolidate food resources from different donors. Therefore, when planning focuses on accurately calculating the required quantity in kilograms to restock their inventory, it falls under single-product planning. Several scholarly inquiries have tackled this aspect of single-product planning, exemplified by the works of Moran et al. [11], Orgut et al. [12], Orgut et al. [15], Haznain et al. [20], Yuanzheng et al. [21], Firouz et al. [22].

However, some food banks uniquely grapple with determining replenishment needs for different donated products. This requires the

development of multi-product planning models. In response to this imperative, Savar et al. [13] undertake the formidable task of addressing the complexities of replenishing products with expiration dates within a multi-product, multi-period framework, all while adhering to the First-Expired, First-Out (FEFO) policy. Their approach aptly accounts for shortage costs and the capacity constraints inherent to the warehousing process. Considering nutritional requirements in optimization models has a relevant impact on the effectiveness and efficiency of resource allocation. In this sense, Cuevas and Gómez [14] address the multi-product, multi-period scenario and offer a food allocation system that considers the availability and dimensional-nutritional characteristics of the food items, as well as the daily energy requirements of the families they serve. However, it is noteworthy that their research does not encompass policies related to inventory shortages or food waste. In Table 1 a summary of the related research works is presented.

The present work proposes a model to address the identified research gaps for multi-product multi-period allocation for perishable products, each with a specified expiry date. This investigation embraces two primary elements: (i) the integration of the First Expiry, First Out (FEFO) policy for the warehouse as an efficient selection criterion for perishable products and (ii) the consideration of critical components, including shortage management, prioritization, nutritional contribution, and labor allocation. This mathematical model allows monitoring and managing each product's dispatch and inventory levels throughout their remaining shelf life at each period within the planning horizon.

3. Motivation and contribution

Akkerman et al. [23] provides an overview of the key supply chain challenges in food bank supply chains. These challenges and their references are presented in Table 2, which corresponds to Table 1 from Akkerman et al. [23]. In this Section, we further complement these challenges from the perspective of donation shortages, the impact of limited labor resources, and considering that products have a limited shelf life and must be allocated promptly. This reality is faced by food banks in developing countries, highlighting the need for tools that allow timely and effective decision-making.

3.1. Supply-side challenges

In the economies of developing countries, securing sufficient food donations to meet the requirements of all beneficiaries can be even more difficult than in developed countries where different collection strategies are used [24–27,33]. Therefore, it becomes increasingly important to ensure that warehouse operations are conducted efficiently and, to the extent possible, equitably. Suppose there is an insufficient quantity of a particular food item to meet the minimum requirements of each beneficiary. In that case, allocating the food based on a predefined criterion is advisable. This approach helps to prevent unnecessary time losses. In this context, maximizing the quantity to be dispatched and minimizing the wastage of products in good condition is crucial [24]. Donation management in the warehouse becomes complex due to the scenario described.

3.2. Supply–demand matching challenges

Typically, foods with higher nutritional value, such as fruits and vegetables, arrive at the food bank's warehouse with a limited shelf life, complicating the warehouse operations [14,19,27]. Additionally, the deficient technological infrastructure makes difficult the traceability of donations [33]. Therefore, adopting a First-Expired, First-Out (FEFO) policy is imperative to select which foods to dispatch to which group of beneficiaries. Ensuring the food security of individuals served by beneficiary agencies is the priority [31–33]. It is essential to avoid foodborne infections, especially among vulnerable age groups such as children and older adults, at all costs. It is important to remember

that the food bank operates in a context where the healthcare system exhibits deficiencies.

In the present work, the distribution of products to beneficiaries is not considered. The operational procedure entails beneficiaries sending their vehicles to the food bank to collect donations. The warehouse determines the quantity and variety of such donations. The food bank relies on unpredictable and voluntary labor [24,25,35] to load the beneficiaries' vehicles, adding another layer of complexity on the operations. Typically, within the context in which the food bank operates, these vehicles are of little tonnage. Economically, it is advantageous for beneficiaries to maximize the capacity of their vehicles and avoid incurring unnecessary travel costs. If the food bank cannot provide the minimum required quantities for a beneficiary, it is essential to communicate this information as promptly as possible. This way, the beneficiary can seek an alternative food source to meet the needs of the vulnerable individuals they serve.

3.3. Demand-side challenges

Each beneficiary institution has distinct nutritional requirements based on the demographics they serve [17]. Satisfying all these nutritional needs can be challenging, and the primary task is to minimize the gap between the required and allocated resources for each beneficiary. Food banks frequently encounter logistical barriers that impede their outreach to the entirety of those in need, either for location decisions [28] or operational difficulties [29,30], highlighting the critical role of allocation in addressing this disparity. The diversity in nutritional needs necessitates a nuanced approach to food distribution, demanding that food banks balance their available supply and the varying dietary requirements of the communities they serve [19]. Addressing these multifaceted challenges mandates meticulous planning and adaptability to ensure that food banks can effectively fulfill their mission of mitigating hunger and advancing food security.

3.4. Contributions

What distinguishes this paper from other studies in literature is a mathematical model that considers the following:

1. A multi-product, multi-period inventory system where each product may possess distinct expiry dates. This system requires labeling of the precise duration in days remaining until expiration, as well as the quality level of the products after being a specific number of days on the shelf. Accordingly, products that have reached their expiry date or do not meet the minimum required quality level must be removed from consideration during the dispatch and allocation process. This information is imperative for managers to prevent dispatching expired items to beneficiary institutions.
2. The allocation of workforce hours per day directly impacts the warehouse's operational efficiency. The available workforce hours are heavily linked to the warehouse's dispatch capacity. Operational activities within the warehouse heavily depend on the participation of volunteers. The proposed model allows for the estimation of how fluctuations in volunteer numbers affect the two key metrics of the system: the daily dispatch volume in kilograms and the amount of expired products or waste.
3. In a scenario characterized by an insufficient inventory to fulfill all beneficiaries' demands, the allocation of quantities for dispatch is determined based on predefined criteria. We deal with real-world limitations (insufficient inventory), which significantly impact the service level of the food bank.
4. This paper addresses the challenge of minimizing disparities between the nutritional content of distributed food items and the nutritional needs of the beneficiaries. These requirements are computed based on the number of individuals and their age range.

Table 1

Characteristics of earlier studies.

Author(s)	Supply stochastic arrival	Period		Product		Product type		Modeling methodology	Objective function	Warehouse policy	Decision variables	Solution approach	Insufficient inventory policy	Nutritional requirements	Waste
		Single	Multi	Single	Multi	Unlimited lifetime	Deteriorating								
Mohan et al. (2013)	✓	✓		✓		✓		Simulation	Max mouths fed, Min waste	None	X	S			✓
Orgut et al. (2015)		✓		✓		✓		LP	Min undistributed supply	None	X	HU			✓
Sazvar et al. (2016)			✓		✓		✓	NLP	Min cost	FEFO	R	GA			✓
Cuevas and Padilla (2017)	✓	✓			✓		✓	MILP, FMILP	Max kilocalories	None	X	E		✓	
Orgut et al. (2018)		✓		✓		✓		LP	Max shipped food	None	I; X	RO; E			
Fianu and Davis (2018)	✓		✓	✓			✓	MDP	Max equity in distribution	None	I; X	DP			
Gómez-Pantoja et al. (2020)		✓			✓	✓		IP	Max beneficiary score	None	X; P	HU; E		✓	
Castanon et al. (2020)		✓			✓	✓		LP	Min cost and unmatched nutrients	None	UN; P	E		✓	
Alkaabneh et al. (2021)	✓		✓		✓	✓		MILP	Max utility	None	I; X	DP		✓	
Hasnain et al. (2021)		✓		✓		✓		LP	Max efficiency, equity	None	X	HU			✓
Yuanzheng et al. (2022)	✓		✓	✓			✓	DP	Min cost, Max fairness allocation	None	I; X	DP; HU			✓
Firouz et al. (2022)		✓		✓		✓		LP	Max efficiency, penalizes deviations	None	X	HU			✓
Current work (2024)			✓		✓		✓	MILP	Max dispatch, Min wastage	FEFO	X	DP	✓	✓	✓

R: Replenishment (Quantity order of product p at period t)

NLP: Nonlinear Programming

HU: Heuristic

X: Dispatch (Quantity of product i to be shipped/dispatch to beneficiary j)

MILP: Mix-Integer Linear Programming

GA: Genetic algorithm

P: Purchased product (Purchased units of product m)

LP: Linear Programming

E: Exact method

I: Inventory (Available inventory at time t)

IP: Integer Programming

DP: Dynamic Programming

UN: Unmatched nutrients (Quantity of unmatched nutrient for the particular beneficiary group)

FMILP: Fuzzy Mixed-Integer Linear Programming

RO: Robust Optimization

MDP: Markov Decision Process

S: Simulation.

Table 2
Main supply chain challenges in food bank supply chains, taken from Akkerman et al. [23].

Supply-side challenges [24–27]	Demand-side challenges [17,19,28–30]
Obtaining sufficient food donations	Difficulty in reaching the potential beneficiary
Irregularity in donation offers	Heterogeneity in dietary requirements of beneficiaries
Waste reduction strategies of donors reduce food available for donations	Beneficiaries do not always use all donated products
Competing uses for surplus food	Adverse effects of global developments and shocks
Perceived donor risk in donating	
Supply–demand matching challenges	
<i>Perishability and food safety</i> [31–33]	<i>Information technology (IT)</i> [33]
Short remaining shelf life of donations	Often limited IT infrastructure
Need to comply with traceability requirements	Easy solutions required for volunteers
<i>Health and food safety</i> [14,19,27]	<i>Transportation and logistics</i> [34]
Difficult to match actual donations with nutritional goals	Lack of coordination of transport activities
Difficult to incentivize healthier products	Increased transportation cost
<i>Voluntary labor</i> [24,25,35]	<i>Supply chain coordination</i>
Limited availability of voluntary labor	Lacking transparency in supply chain
Diverse and uncertain skillset among volunteers	Many unconnected initiatives
	Complexity in achieving equitable food support

4. Model development

This Section details assumptions and definitions before formulating the mixed integer programming model. We do want to emphasize that our discussion is limited to the operations in the warehouse.

4.1. Problem description

The problem involves efficiently managing donated perishable products within a finite planning time horizon of T days. When a product arrives from a donation institution, a mandatory processing period of one day is required. This processing includes tasks like categorizing, cleaning, and labeling quality levels and expiration dates of incoming donations. Products can be classified into two groups:

1. **Highly perishable food:** These include vegetables and fruits obtained from city markets. Generally, these products have a few days of shelf life left before expiration. Once inspected and any damaged items are removed, they are stored in a cold storage room to ensure better preservation.
2. **Perishable food:** This group comprises foods with weeks or months before expiration. Supermarkets and food manufacturers donate food they cannot sell anymore, as detailed in Akkerman et al. [23]. For instance, when supermarkets may have predicted wrongly the demand or when a production batch from manufacturers received the wrong labels.

The length of the planning period is six days. A critical element is the number of volunteers available for each warehouse operation day. The volunteers' tasks include product sorting, quality control, expiration date labeling, and dispatch. Therefore, the available number of volunteers directly impacts the warehouse's performance. Donations can be received at the food bank warehouse any day during the planning period. The approach to be considered for the dispatch process follows a First Expired-First Out (FEFO) policy.

In other words, products with a shorter remaining lifetime must be allocated and dispatched earlier than similar products with a longer remaining lifetime. To model this requirement, we define a parameters that show the remaining lifetime before expiration and the minimum quality level of the products that arrive at the warehouse. The expired products will be transferred to landfill sites or other sites for recycling, while products that no longer meet the minimum quality will be sent for further processing steps. Regarding the limitations in terms of budgets, it is essential to dispose of an accurate estimation of the waste.

The responsibility of collecting products from the warehouse falls upon the beneficiary institutions. Due to operational constraints – such as the receipt of limited quantities of products, a shortage of volunteers, and products with a few days remaining before expiration – the food

bank strategically allocates products and corresponding amounts to be collected by beneficiary organizations. When the available inventory is insufficient to fulfill beneficiary demand, a prioritization criterion comes into play when deciding on product allocation. Notably, the food bank's warehouse has an unrestricted total capacity, allowing for the storage of all donations. All product measurements are expressed in kilograms.

Given the multiple constraints in this Section, the problem is determining the kilogram quantity to be dispatched per product, day, and beneficiary to fulfill its nutritional requirements. While safety food is strongly encouraged, the proposed model developed in the following sections and its corresponding implementation intends to provide a planning tool for the operations in the food bank warehouse. The model can be categorized as a multi-period, multi-product, for perishable products by considering the dynamic arrival of products to the warehouse under limitations of workforce and supply levels.

4.2. Assumptions

To formulate the MILP problem, the following assumptions were considered:

- The planning time horizon is finite and consists of T days.
- Donations can arrive any day within the planning period.
- A First Expired-First Out (FEFO) policy is considered for the dispatch process.
- Each product may have different lifetimes.
- Shelf life impacts product quality. Products that fail to meet minimum quality standards, defined by the warehouse management, are not distributed to beneficiaries. Unexpired products may be repurposed.
- Upon the arrival of a product from donation institutions, a processing period of one day is necessary. The receiving process entails tasks such as classification, cleaning, and labeling of the quality level and the expiration date. A detailed explanation of this process can be found in Feeding America's Produce Handling Toolkit [36], as well as a way to determine the quality level of vegetables and fruits as noted by Tijssens et al. [37].
- Beneficiary institutions are in charge of collecting the products from the warehouse.
- Due to the operational context of the food bank, which involves receiving limited product quantities, a small number of volunteers, and items with only a few days left before expiration, the food bank allocates products and their respective amounts that the beneficiary institutions will collect.
- Each beneficiary has a minimum required demand per product and day. This amount was determined by the number of people supported by the beneficiary institution.

Table 3
Model notations.

Set	Description
I	Set of products
J	Set of beneficiaries
T	Set of dispatch days
P	Set of product arrival days
V	Set of nutrients
Parameter	Description
$D_{i,j,t}$	Minimum demand of product $i \in I$ from beneficiary $j \in J$ during period $t \in T$
$\theta_{j,v}$	Demand of nutrient $v \in V$ from beneficiary $j \in J$
$\theta_{j,v}^{MAX}$	Maximum allowed amount of nutrient $v \in V$ from beneficiary $j \in J$
$a_{i,v}$	Amount of nutrient $v \in V$ provided by 100 g of product $i \in I$
$Q_{i,p}$	Quantity of product $i \in I$ in kilograms received during time period $p \in P$. When $p = 0$, $Q_{i,p}$ represents the initial inventory at the beginning of the planning period.
H_i	Required time in minutes to dispatch 1 kg of product $i \in I$
L_t	Total available hours to dispatch products in $t \in T$
$e_{i,t,p}$	Binary parameter, $e_{i,t,p} = 1$ if and only if product $i \in I$ that arrived on $p \in P$ is expired in $t \in T$
$u_{i,p}$	Number of days before expiration of product $i \in I$ that arrived in $p \in P$
$\rho_{i,t}$	Quality level of product $i \in I$ after being t days on shelf.
$q_{i,t-p}^{MIN}$	Lowest required quality level for approving the dispatch of product $i \in I$, after being $t - p$ days on shelf for $t \in T$ and $p \in P$.
Variable	Description
$x_{i,j,t,p}$	Quantity in kilograms to dispatch of product $i \in I$ to beneficiary $j \in J$ on day $t \in T$, that arrived to the warehouse in $p \in P$
$n_{i,t,p}$	Available inventory of product $i \in I$ that arrived to the warehouse in $p \in P$ at the end of day $t \in T$
$w_{i,t,p}$	Quantity of product $i \in I$ that arrived on $p \in P$, expires at the end of day $t \in T$, and cannot be dispatched starting from t . This variable represents the waste or the amount of product expired before its dispatch.
$y_{i,j,t}$	Fraction of product $i \in I$ demand dispatched to beneficiary $j \in J$ in $t \in T$. $y_{i,j,t} \in [0, 1]$.
$l_{i,t}$	Binary variable, $l_{i,t} = 1$ if and only if inventory of product $i \in I$ is lower or equal than the total minimum demand $\sum_{j \in J} D_{i,j,t}$ in $t \in T$.
$r_{v,j}$	Variable that represents the difference between the nutritional requirement and the supplied amount of nutrient $v \in V$ to the beneficiary $j \in J$.
$q_{i,t,p}$	Quality level of product $i \in I$ that arrived at the warehouse on the day $p \in P$ and has been on the shelf until the end of the day $t \in T$
$k_{i,t,p}$	Quantity of product $i \in I$ that arrived on the day $p \in P$ and does not meet the minimum quality requirement at the end of the day $t \in T$. This product cannot be dispatched starting from day $t + 1 \in T$.

- Nutritional requirements from the beneficiary institutions.
- The initial inventory level for each product can be either positive or zero.
- In the case of insufficient inventory to meet beneficiary demand, a prioritization criterion is considered for product allocation.
- The total capacity of the food bank's warehouse is unlimited.
- The unit of measurement for the products is in kilograms.
- Each beneficiary should not receive more of any nutrient than its specific nutritional needs as it is considered in the formulation proposed by Martins et al. [38]

4.3. Notations

The notation of parameters and decision variables are listed and explained in Table 3 and Fig. 1 shows the allocation system for received donations.

4.4. Multi-objective optimization model

In this Section, we detail the problem's constraints and objective function of the problem.

Inventory balance constraints: Constraints (1) and (2) update the available inventory at the end of day $t \in T$ and ensure that only non-expired products can be dispatched. There are two cases:

$$n_{i,t,p} = e_{i,t,p} \left(Q_{i,p} - \sum_{j \in J} x_{i,j,t,p} \right) \quad \forall i \in I \quad \forall t \in T \quad p = t - 1 \quad p \in P \quad (1)$$

$$n_{i,t,p} = e_{i,t,p} \left(n_{i,t-1,p} - \sum_{j \in J} x_{i,j,t,p} \right) \quad \forall i \in I \quad t \in T \quad p < t - 1$$

$$p \geq 1 \quad t \geq 2 \quad p \in P \quad (2)$$

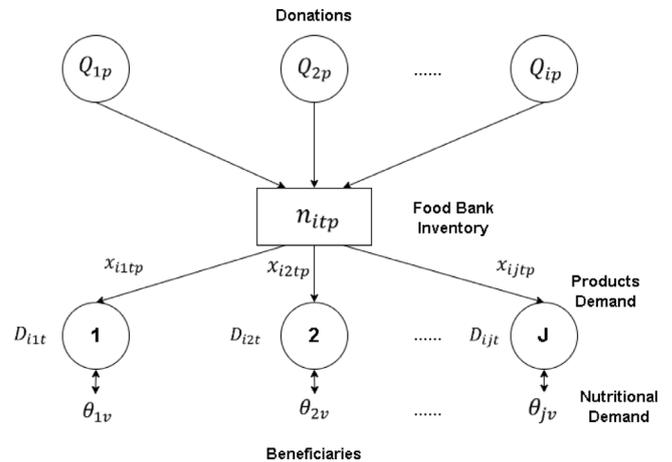


Fig. 1. Food Bank allocation system.

Constraints (1) establish when the product to be dispatched arrives the previous day; the available inventory corresponds to $Q_{i,p}$. Constraints (2) establish when the product to be dispatched arrives at least one day before the day prior ($p < t - 1$), the available inventory for dispatch on t corresponds to $n_{i,t-1,p}$. In both sets of constraints, we observe the binary parameter $e_{i,t,p}$ on the left-hand side. This parameter ensures the variable $n_{i,t,p}$ becomes zero when product $i \in I$, which arrived on $p \in P$, is expired on $t \in T$.

Maximum allowed person-hours of work: At the beginning of the planning period of T days, the maximum allowed number of person-hours of work per day L_t $t \in T$ is known. Constraints (3), ensure that L_t cannot be exceeded.

$$\sum_{p=0}^{t-1} \sum_{j \in J} \sum_{i \in I} H_i x_{i,j,t,p} \leq L_t \quad \forall t \in T \quad (3)$$

Maximum available dispatch: The amount of product to dispatch must not exceed the maximum available product. This condition is imposed by:

$$\sum_{j \in J} x_{i,j,t,p} \leq Q_{i,p} \quad \forall i \in I \quad \forall t \in T \quad p = t-1 \quad p \in P \quad (4)$$

$$\sum_{j \in J} x_{i,j,t,p} \leq n_{i,t-1,p} \quad \forall i \in I \quad \forall t \in T \quad p < t-1 \quad p \in P \quad (5)$$

Constraints (4) ensure that when the product $i \in I$ arrives on the day before shipment on $t \in T$, i.e., $p = t-1$, the maximum quantity available for dispatch is $Q_{i,p}$. Similarly, constraints (5) ensure that the quantity available for dispatch is $n_{i,t-1,p}$ when product $i \in I$, to be dispatched at $t \in T$, arrives at the warehouse on day $p \in P$, where $p < t-1$.

Insufficient inventory: It is possible that, for some days, the available inventory may not be sufficient to meet the minimum requirements of each beneficiary. In such situations, the available quantity of products must be redistributed. The procedure for reallocating the available inventory will be detailed in this Section 4.5.

$$Q_{i,p} \leq \sum_{j \in J} D_{i,j,t} + M(1 - l_{i,t}) \quad \forall i \in I \quad t \in T \quad t = 1 \quad p \in P \quad p = 0 \quad (6)$$

$$Q_{i,p} \geq \sum_{j \in J} D_{i,j,t} - M l_{i,t} \quad \forall i \in I \quad t \in T \quad t = 1 \quad p \in P \quad p = 0 \quad (7)$$

$$\sum_{p < t-1} n_{i,t-1,j} + Q_{i,t-1} \leq \sum_{j \in J} D_{i,j,t} + M(1 - l_{i,t}) \quad \forall i \in I \quad t \in T \quad t > 1 \quad (8)$$

$$\sum_{p < t-1} n_{i,t-1,j} + Q_{i,t-1} \geq \sum_{j \in J} D_{i,j,t} - M l_{i,t} \quad \forall i \in I \quad t \in T \quad t > 1 \quad (9)$$

When it is impossible to meet all beneficiaries' demand for the product $i \in I$ on the day $t \in T$, the model allows us to identify it by using the binary variable $l_{i,t}$. Constraints (6)–(9) constitute an application of the Big M method for constraints in a linear optimization problem. The Big M technique introduces logical exclusive constraints, ensuring the problem remains feasible. By using a sufficiently large number M and binary variables, conflicts between constraints are avoided, thus preventing the infeasibility of the problem. The planning horizon has been divided into two cases: the first day, i.e., $t = 1$, and the remaining days, i.e., $t = 2, \dots, T$. Constraints (6) and (7) correspond to the first case, while constraints (8) and (9) belong to the second case. The left-hand side of constraints (6) and (7) is the feasible inventory for the day $t = 1$. This inventory corresponds to the amount of product available at $p = 0$, i.e., the initial inventory of the planning horizon. When $l_{i,t} = 1$, constraints (6)–(9) establish that the available inventory does not exceed the lowest required demand for $t = 1$. In other words, the available inventory is insufficient to meet the beneficiaries' requirements. In contrast, for $l_{i,t} = 0$ constraints (6)–(9) indicate the available inventory is enough to satisfy the beneficiaries' requirements.

Sufficient inventory: Constraints (10) ensure that on day $t \in T$, when the available inventory of product $i \in I$ is sufficient to meet the minimum demand, that is, when $l_{i,t} = 0$, the quantity to dispatch to beneficiary $j \in J$ must be greater or equal than to the minimum required demand.

$$\sum_{p=0}^{t-1} x_{i,j,t,p} \geq D_{i,j,t}(1 - l_{i,t}) \quad \forall i \in I \quad \forall t \in T \quad \forall j \in J \quad (10)$$

Update of waste: The model allows computing the waste, corresponding to the quantity of available inventory at the end of the day $t \in T$ that will expire on day $t + 1$. The expiration day of product $i \in I$, which

arrived on the day $p \in P$, is calculated using the number of days until its expiration $U_{i,p}$. Therefore, waste is updated by the equation:

$$w_{i,t,p} = n_{i,t,p} \quad \forall i \in I \quad \forall p \in P \quad t \in T \quad t = p + U_{i,p} \quad (11)$$

Nutritional requirements: Each food bank beneficiary supports a group of vulnerable individuals with diverse nutritional needs. To meet these needs in the best possible way, it is proposed that nutritional requirements be taken into account when allocating products to the beneficiaries. To achieve this, we suggest minimizing the difference between the nutritional requirements and the nutritional contribution of the dispatched products. It is challenging to fulfill all nutritional needs in a context such as the one in which food banks operate in developing countries. Therefore, the difference between the nutritional contribution of the products dispatched by the food bank and the requirements from the beneficiary institutions is a critical measure to consider. Such difference corresponds to the absolute value in the left-hand side of the inequality (12). To minimize this absolute value and integrate it into the proposed model, we incorporate it as a new set of constraints, where the right-hand side is a decision variable, denoted by $r_{v,j}$, serving as an upper bound for the difference. By minimizing this variable in the objective function, we aim to reduce the mentioned difference.

$$\left| \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{p \in P} a_{i,v} x_{i,j,t,p} - \theta_{j,v} \right| \leq r_{v,j} \quad \forall v \in V \quad \forall j \in J \quad (12)$$

Once the absolute value is removed, the new constraints are:

$$\sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{p \in P} a_{i,v} x_{i,j,t,p} - \theta_{j,v} \leq r_{v,j} \quad \forall v \in V \quad \forall j \in J \quad (13)$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{p \in P} a_{i,v} x_{i,j,t,p} - \theta_{j,v} \geq -r_{v,j} \quad \forall v \in V \quad \forall j \in J \quad (14)$$

The last nutritional aspect to consider is to prevent people from beneficiary institutions from receiving excessive nutrients that may adversely impact their health, the subsequent set of constraints limits the maximum amount of nutrients to be dispatched:

$$\sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{p \in P} a_{i,v} x_{i,j,t,p} \leq \theta_{j,v}^{MAX} \quad \forall v \in V \quad \forall j \in J \quad (15)$$

Dispatch requirements: Constraints (16) and (17) ensure that at least one product is dispatched and at least one beneficiary be served during the planning period of T days.

$$\sum_{t \in T} \sum_{j \in J} y_{i,j,t} \geq 1 \quad \forall i \in I \quad (16)$$

$$\sum_{t \in T} \sum_{i \in I} y_{i,j,t} \geq 1 \quad \forall j \in J \quad (17)$$

Quality impact: Constraints (18)–(20) allow assigning a quality level for product $i \in I$ arriving on day $p \in P$, that is in stock at the end of the day $t \in T$. Eqs. (18), when $n_{i,t,p}$ is not equal to zero, assign a quality level to products based on the number of days they have been on the shelves. The quality level of a product that arrived in p and has been on the shelf for $t - p$ days is represented by a piece-wise linear function to capture the non-linear behavior of its degradation over time. When $n_{i,t,p}$ equals zero, a sufficiently large value is assigned allowing the problem to remain feasible. To do this, we will use the binary variable $c_{i,t,p}$, which takes the value of 1 whether the inventory $n_{i,t,p}$ is strictly positive, and a parameter ϵ which takes a value close to 0. When $n_{i,t,p}$ is equal to zero, constraints (19) and (20) ensure that the binary variable $c_{i,t,p}$ is equal to zero so that the quality level will take a sufficiently large value to guarantee the feasibility of the problem. On the other hand, when $n_{i,t,p}$ is greater than zero, the parameter epsilon forces the binary variable $c_{i,t,p}$ to be equal to 1. Therefore, Eqs. (18) will assign quality levels to $q_{i,t,p}$ for some $i \in I$, $t \in T$, and $p \in P$.

$$q_{i,t,p} = \rho_{i,t-p} + M(1 - c_{i,t,p}) \quad \forall i \in I \quad \forall t \in T \quad p \in P \quad p < t \quad (18)$$

$$n_{i,t,p} \leq M c_{i,t,p} \quad \forall i \in I \quad \forall t \in T \quad p \in P \quad p < t \quad (19)$$

$$n_{i,t,p} \geq \epsilon c_{i,t,p} \quad \forall i \in I \quad \forall t \in T \quad p \in P \quad p < t \quad (20)$$

When the minimum quality level is not met, the corresponding product must be sent to waste due to its degradation on the shelf. To consider this scenario, we introduce the binary variable $h_{i,t,p}$, which takes the value of 1 when $q_{i,t,p}$ is less than $q_{i,t,p}^{MIN}$, and 0 when the condition $q_{i,t,p} \geq q_{i,t,p}^{MIN}$ is satisfied. Therefore, when the condition $q_{i,t,p} \geq q_{i,t,p}^{MIN}$ is not satisfied, the amount to send to waste is $n_{i,t,p}h_{i,t,p}$, which is a nonlinear expression. To linearize this expression, we introduce the variable $k_{i,t,p} = n_{i,t,p}h_{i,t,p}$ and the constraints (22)–(24). We observe that if the quality condition $q_{i,t,p} \geq q_{i,t,p}^{MIN}$ is not met, $k_{i,t,p} = n_{i,t,p}$, otherwise 0. Constraints (25) ensure that when there is no available inventory at the end of the day $t \in T$, $k_{i,t,p}$ is zero. Finally, constraints (26) prevent the dispatch in the day t of products that do not meet the quality conditions at the end of day $t - 1$.

$$q_{i,t,p} \geq q_{i,t-p}^{MIN} - Mh_{i,t,p} \quad \forall i \in I \quad \forall t \in T \quad p \in P \quad p < t \quad (21)$$

$$k_{i,t,p} \leq n_{i,t,p} + (1 - h_{i,t,p})M \quad \forall t \in T \quad p \in P \quad p < t \quad (22)$$

$$k_{i,t,p} \geq n_{i,t,p} - (1 - h_{i,t,p})M \quad \forall t \in T \quad p \in P \quad p < t \quad (23)$$

$$k_{i,t,p} \leq Mh_{i,t,p} \quad \forall t \in T \quad p \in P \quad p < t \quad (24)$$

$$h_{i,t,p} \leq c_{i,t,p} \quad \forall t \in T \quad p \in P \quad p < t \quad (25)$$

$$\sum_{j \in J} x_{i,j,t,p} \leq M(1 - h_{i,t-1,p}) \quad \forall i \in I \quad t \geq 2 \quad t \in T \quad p \in P \quad p < t - 1 \quad (26)$$

Objective Function: During the development of the constraints, we observe four elements to consider in the objective function. First, the dispatch denoted as $x_{i,j,t,p}$. When the dispatch increases, according to the constraints (1) and (2), the inventory level and waste decrease. Maximizing dispatch should prioritize products with the shortest remaining shelf life. The second element embraces the decision variables $r_{v,j}$, the difference between the dispatches' nutritional contribution and the beneficiaries' nutritional requirements. The third aspect to consider in the objective function is the minimization of shortages. It is convenient to avoid situations where there is over-dispatch on one day and shortages the next day. The last element to consider is the amount of products that do not meet the minimum quality requirements to be dispatched to the beneficiaries. The nature of these four factors leads us to a multi-objective optimization problem. To consider the warehouse's First Expired, First Out (FEFO) policy, we use $\frac{1}{u_{i,p}}$ as the coefficient of $x_{i,j,t,p}$. Thus, priority in dispatch will be given to products with fewer remaining days of shelf life, contributing to safeguarding food security. When the number of days before expiration $u_{i,p}$ decreases, its negative reciprocal $-\frac{1}{u_{i,p}}$ also decreases; thus, minimizing $-\frac{x_{i,j,t,p}}{u_{i,p}}$ results in greater values of $x_{i,j,t,p}$ for products with a lower shelf life. By using this approach, the impact of the shelf life of each product is included in the objective function through a penalty for the corresponding decision variables. The last goal is to minimize the shortage. To do this, let us review the following difference for $l_{i,t} = 1$:

$$g_{i,t} = \sum_{j \in J} D_{i,j,t} - \sum_{j \in J} \sum_{p < t} x_{i,j,p,t} \quad \forall i \in I \quad \forall t \in T$$

The variable $g_{i,t}$ is greater than zero for some $i \in I$ and $t \in T$, when the inventory is insufficient to meet the demand. Therefore, to deal with the shortage, it is necessary to minimize:

$$\sum_{i \in I} \sum_{t \in T} g_{i,t} l_{i,t}$$

The expression presented above is nonlinear and can be linearized by introducing the decision variable $b_{i,t} = g_{i,t} l_{i,t}$ for all $i \in I$ and $t \in T$. Also, to ensure that $b_{i,t} = g_{i,t} l_{i,t}$ hold for both $l_{i,t} = 0$ and $l_{i,t} = 1$ for all $i \in I$ and $t \in T$, four additional constraints are added:

$$b_{i,t} \leq M l_{i,t} \quad \forall i \in I \quad \forall t \in T \quad (27)$$

$$g_{i,t} \geq -M(1 - l_{i,t}) + b_{i,t} \quad \forall i \in I \quad \forall t \in T \quad (28)$$

$$g_{i,t} \leq M(1 - l_{i,t}) + b_{i,t} \quad \forall i \in I \quad \forall t \in T \quad (29)$$

$$g_{i,t} = \sum_{j \in J} D_{i,j,t} - \sum_{j \in J} \sum_{p < t} x_{i,j,p,t} \quad \forall i \in I \quad \forall t \in T \quad (30)$$

When $l_{i,t} = 1$, constraints (28) and (29) ensure that $b_{i,t} = g_{i,t} l_{i,t}$. When $l_{i,t} = 0$, constraint (27) guarantee that $b_{i,t} = 0 = g_{i,t} l_{i,t}$. Denote by $F(f_1, f_2, f_3, f_4)$ the vector of objectives functions to minimize. The multi-objective function is as follows:

$$\min \quad F(f_1, f_2, f_3, f_4)$$

$$\text{where :} \quad f_1 = \sum_{v \in V} \sum_{j \in J} r_{v,j}$$

$$f_2 = - \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{p \in P} \frac{1}{u_{i,p}} x_{i,j,t,p}$$

$$f_3 = \sum_{i \in I} \sum_{t \in T} b_{i,t}$$

$$f_4 = \sum_{i \in I} \sum_{t \in T} \sum_{p \in P} k_{i,t,p}$$

To solve the multi-objective problem, f_1, f_2, f_3 , and f_4 are scaled to force that they have the same units and range. The scalarization process is carried out by applying the linear normalization technique introduced by Ransikarbum and Mason [39]. This technique involves converting the objective function values into a range between zero and one, using the largest and lowest values that the objective functions f_i $i = 1, 2, 3, 4$ can achieve. As the four objectives after normalization are transformed into a minimization problem, we can then use the weighted objective method as follows:

$$\min \alpha_1 \frac{f_1 - f_1^L}{f_1^U - f_1^L} - \alpha_2 \frac{f_2 - f_2^L}{f_2^U - f_2^L} + \alpha_3 \frac{f_3 - f_3^L}{f_3^U - f_3^L} + \alpha_4 \frac{f_4 - f_4^L}{f_4^U - f_4^L}$$

By varying α_i $i = 1, 2, 3, 4$ from 0 to 1 such as $\sum_{i=1}^4 \alpha_i = 1$, the model can be solved to obtain non-dominated solutions and the approximate Pareto frontier curve and allow the food bank managers to evaluate trade-offs between maximizing the dispatch in kilograms and the gap between nutritional requirements from beneficiaries and the provided nutrients.

After solving the mixed integer programming problem introduced in this section, our focus shifts to instances where $l_{i,t} = 1$, that is, insufficient available inventory to meet the demand. Utilizing a score-based criterion, we ascertain which beneficiaries will receive the minimum required demand as an outcome of an integer optimization sub-problem. In the subsequent section, we will demonstrate that these sub-problems satisfy optimal substructure and overlapping conditions, being them suitable for efficient resolution through Dynamic programming.

4.5. Insufficient inventory and dynamic programming

In this Section, we address the scenery of insufficient food inventory using a dynamic programming approach. This technique involves an implicit enumeration for solving integer optimization problems. Note that for $l_{i,t} = 1$, the constraints (8) and (10), derive the following set of inequalities:

$$Q_{i,p} \leq \sum_{j \in J} D_{i,j,t} \quad i \in I \quad t \in T \quad t = 1 \quad p \in P \quad p = 0 \quad (31)$$

$$\sum_{p < t-1} n_{i,t-1,p} + Q_{i,t-1} \leq \sum_{j \in J} D_{i,j,t} \quad i \in I \quad t \in T \quad t > 1 \quad (32)$$

The left-hand side of inequalities (31) and (32) corresponds to the available inventory. Consequently, when $l_{i,t} = 1$, it means that the available inventory is lower or equal to the total minimum required demand for a product $i \in I$ for the day $t \in T$. It is important to remember that the calculation of the lowest allowable demand is determined based on the minimum required load for transportation and the minimum requirement of the beneficiary.

In cases where an insufficient food supply is available, the food bank must promptly communicate with the intended beneficiaries to

indicate which can send vehicles to the warehouse and which must look for a different source of food. To determine the eligibility, a score system is computed for each beneficiary, which aids in prioritizing the dispatch process. This scoring mechanism takes into account the following criteria:

- 1 Vulnerability.
- 2 Urgency of current need.
- 3 Age group of the beneficiary's members.

For the present work, in the numerical experiment section, a case-based system is detailed for the computation of the score for each beneficiary. In the context of a product $i \in I$ with insufficient inventory at day $t \in T$, multiple prioritizations must be undertaken to determine which beneficiaries will pick up products from the warehouse. The resolution of this selection is based on the scoring system previously presented. The idea is to redistribute the total amount of product i dispatched on the day t when $l_{i,t} = 1$, formulating this allocation as an integer optimization problem. In this formulation, the objective function is the sum of scores for beneficiaries who will receive their minimum required demand $D_{i,j,t}$, subject to the total quantity to be dispatched does not exceed the total to dispatch, which corresponds to the total to dispatch according to the solution of the problem presented in the previous section. This product allocation constitutes an application of the classic Knapsack- $\{0, 1\}$ problem. The number of integer optimization problems to be solved depends on the value that the decision variable $l_{i,t}$ $i \in I$ $t \in T$ takes after solving the problem formulated in Section 4.4. Let $E = \{(i,t) | l_{i,t} = 1, i \in I, t \in T\}$ be the set of products with insufficient inventory on a determined day. Thus $|E|$ is the number of Knapsack- $\{0, 1\}$ problems that need to be addressed. There may be numerous instances of such problems to address. Consequently, a Dynamic Programming approach is used as it offers the most effective method for solving Knapsack- $\{0, 1\}$ problems.

We next show how the integer problem is formulated. Let s_j be the score for beneficiary $j \in J$, $D_{i,j,t}$ the weight for the items, and $C_{i,t}$ be the capacity of the knapsack. Where $C_{i,t}$ is computed as follows:

$$C_{i,t} = \sum_{j \in J} \sum_{p < t} x_{i,j,t,p}$$

The integer optimization problem is:

$$\begin{aligned} \max \quad & \sum_{j \in J} s_j z_j \\ & \sum_{j \in J} D_{i,j,t} z_j \leq C_{i,t} \\ & z_j \in \{0, 1\} \end{aligned} \quad (33)$$

The discrete redistribution problem (33) exhibits optimal substructure in the following manner:

Claim 1. *Let j be the highest numbered beneficiary in an optimal solution S of the problem (33) for $[C_{i,t}]$ and $j = 1, \dots, |J|$. Then $S' = S - \{j\}$ is an optimal solution for $[C_{i,t}] - D_{i,j,t}$ and beneficiaries $j = 1, \dots, j - 1$.*

Proof. By contradiction, assume there was a better solution for $[C_{i,t}] - D_{i,j,t}$ and beneficiaries $j = 1, \dots, j - 1$ than S' . Then S' can be replaced with this better solution, yielding a feasible solution for $[C_{i,t}]$ kilograms and beneficiaries $j = 1, \dots, |J|$ with larger value of the corresponding objective function than the solution being considered. However, this contradicts the optimality of the given initial solution. ■

Therefore, the optimal solution to the problem (33) is composed of optimal solutions to sub-problems. Next, we recursively define the value of the optimal solution. Given a pair $(i,t) \in E$, the steps for solving the integer problem are the following:

- Decompose the problem into smaller sub-problems.
- Create a lookup table $S[0, \dots, |J|, 0, \dots, [C_{i,t}]]$. Where $|J|$ is the number of beneficiaries and $[C_{i,t}]$ is the knapsack capacity.

- Each entry $S[j, c]$ stores the best value for the subset of the first beneficiaries $\{1, \dots, j\}$ in a knapsack of capacity c .
- Fill table; the entry at $S[|J|, [C_{i,t}]]$ will be the optimal value.

Entry $S[j, c]$ is computed by using the recursive rule:

$$S[j, c] = \begin{cases} S[j-1, c] & \text{if } c_j > c, \\ \max\{S[j-1, c], s_j + S[j-1, c - c_j]\} & \text{otherwise.} \end{cases} \quad (34)$$

Note that $S[0, c] = S[j, 0] = 0$ for all $j \in J$ and $c \in \{1, \dots, [C_{i,t}]\}$. Based on the above steps, the following algorithm computes the optimal solution for the problem (33).

Algorithm 1 DP algorithm for the insufficient inventory allocation problem

input: $s_j [C_{i,t}]$
output: Optimal allocation

```

1:  $k \leftarrow 0$ 
2:  $\lambda \leftarrow -1$ 
3: for  $j = 1, \dots, |J|$  do
4:   for  $c = 1, \dots, [C_{i,t}]$  do
5:     if  $c_j > c$  then
6:        $S[j, c] \leftarrow S[j-1, c]$ 
7:     else
8:        $S[j, c] \leftarrow \max\{S[j-1, c], s_j + S[j-1, c - c_j]\}$ 
9:     end if
10:  end for
11: end for

```

The running time for the Dynamic Programming procedure 1 is $\Theta(|J|[C_{i,t}])$ due to the nested loops (Lines 3 and 4).

The optimal value for the integer problem corresponds to the entry $S[|J|, C_{i,t}]$. The optimal values for the binary variables z_j $j \in J$ are determined by a backtracking search based on whether beneficiary j will pick up its minimum required demand or not. This backtracking procedure is presented in the following algorithm.

Algorithm 2 Algorithm to determine optimal values of z_j

input: $S, [C_{i,t}]$, and $|J|$
output: z_j

```

1:  $j \leftarrow |J|$ 
2:  $k \leftarrow [C_{i,t}]$ 
3: while  $j > 0$  and  $k > 0$  do
4:   if  $S[j, c] \neq S[j-1, c]$  then
5:      $z_j \leftarrow 1$ 
6:      $k \leftarrow k - c_j$ 
7:   else
8:      $z_j \leftarrow 0$ 
9:   end if
10:   $j \leftarrow j - 1$ 
11: end while

```

5. Computational results and case study

We now present the results for our model using real-world data provided by the Diakonia Food Bank, which is located in Guayaquil, Ecuador. The CPLEX MIP solver is used for the model implementation. The whole framework is built by combining C# and CPLEX Concert Technology.

To illustrate the high degree of perishability of the products received by the food bank from donors, we present the following bar graphs:

Fig. 2 shows the quantity in kilograms and the number of days of shelf life before expiration. Additionally, it is relevant to consider that the arriving products require one day for preprocessing, sorting, quality control, and subsequent storage.

The weighted sum strategy presented in Section 4.4 converts the multi-objective problem of minimizing the vector $(f_1, -f_2, f_3, f_4)$ into a scalar problem by constructing a weighted sum of the nutritional

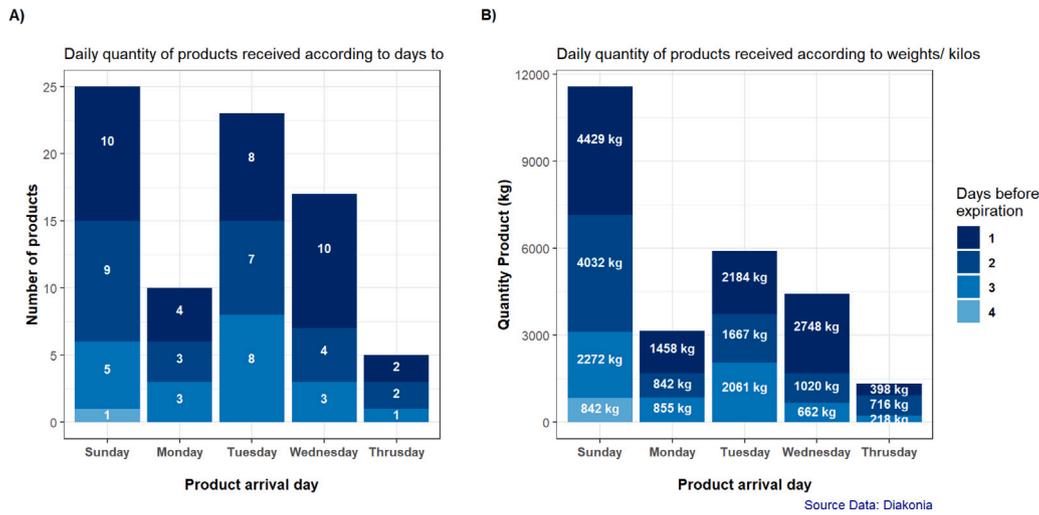


Fig. 2. Arrival of donated product per day.

Table 4
Diakonia instance sets.

Set	Description	Size
I	Products	38
J	Beneficiaries	111
T	Horizon planning	6
V	Nutrients	9

gap and dispatch objectives. The problem is optimized by applying exact methods, integrated with linear solvers. It is worth noting that the normalization and weighting coefficients may not correspond to the relative importance of the objectives or enable explicit trade-offs between them. As mentioned during the model development, a prioritization score is used to redistribute the dispatch when it is not possible to meet the minimum demand per beneficiary. The prioritization score $s_j \forall j \in J$ is based of the following factors:

- Vulnerability of the beneficiary:** Higher scores are assigned to beneficiaries who are in situations of greater vulnerability, such as those facing extreme poverty, critical health issues, or emergencies. Denoted by $VUL_j \forall j \in J$.
- Urgency of current Need:** The urgency of the beneficiaries' current needs is considered, with higher scores awarded to those whose situation requires immediate intervention to meet their basic needs. Denoted by $URG_j \forall j \in J$.
- Person type factor:** Each beneficiary is assigned a person type, with a value of 2 for children and a value of 1 for adults. Denoted by $PF_j \forall j \in J$.

According to the methodology of the food bank, the score is assigned as follows:

$$s_j = PF_j(VUL_j + URG_j) \tag{35}$$

Table 4 shows the size of the sets for the Diakonia food bank case. Table 5 presents the results of the computational experiments generated for the execution of the proposed model. Table 5 displays values of $f_1, f_2, f_3,$ and f_4 for some values of α_i . The "served beneficiaries" column indicates the number of beneficiaries receiving their minimum required demand for the study case scenario, wherein the total quantity to be dispatched during the planning period is distributed. Additionally, execution times in seconds for each multi-objective problem and its corresponding sub-problems are provided, showing that the multi-objective problems can be solved efficiently by using the CPLEX solver. It is worth noting that any day of the week can be considered the initial

day of the planning period. Therefore, if parameters are updated, the new quantity to be dispatched per product can be efficiently obtained. Moreover, when redistributions of quantities of products to dispatch are necessary, the dynamic programming procedure executes within seconds.

To continue the sensitivity analysis, we select one of the solutions from Table 5. We chose the solution corresponding to $\alpha_1 = 0.4, \alpha_2 = 0.2, \alpha_3 = 0.3,$ and $\alpha_4 = 0.1$. It is worth noting that, in the multi-objective model, only the parameter related to labor hours can be influenced by the management of the food bank. Table 6 presents optimal solutions for variations in the number of available personnel during period $T = 6$. The first row, $N = -1$, represents having one fewer person during the whole period. On the other hand, $N = 4$ indicates the presence of four additional individuals to assist with dispatch tasks. The purpose of this analysis is to allow us to quantify the impact of increasing labor hours on dispatch, waste levels, and the amount of products in kilograms that do not meet the minimum required quality level.

In the context of a scarcity of donations, the quantity dispatched in kilograms is the primary performance indicator by which The Global FoodBanking Network monitors the Diakonia Food Bank operations. Sensitivity analysis is pivotal in comprehending how alterations in labor-hour constraints impact the dispatch and waste quantities. Suppose the available labor work hours were to increase or decrease as shown in Fig. 3. In that case, we are particularly interested in quantifying the impact on the amount to dispatch and how many food kilograms will be wasted.

The current optimal solution yields a total dispatch of 25 729.46 kg., corresponding to the baseline scenario with no variations in the number of volunteers. Table 6 provides values for dispatch under different scenarios, ranging from a decrease of one volunteer throughout the entire planning period, denoted as T , to an increase of 9 volunteers per day during T compared to the baseline case. An increment of 4 volunteers per day yields a 17.6% positive variation in dispatch relative to the baseline. Fig. 3 illustrates that the data does not conform to a linear trend, rendering an average increase in kilograms per additional volunteer incorrect. Similarly, we can observe the impact of volunteer variations on the total waste in Table 6. When a volunteer cannot attend the food bank warehouse, there is a 23.9% increase in waste. Conversely, if we have 3 additional volunteers every day during the T period, we observe a reduction of -20.1% in waste. Fig. 4 displays the non-linear behavior of waste variation concerning changes in the number of volunteers per planning period. This methodology enables the analysis of changes on specific days and the quantification of their impact on dispatched products and waste generation. This kind of insight is invaluable for decision-makers, as it helps them assess the

Table 5
Results of the computational experiment of the proposed model.

$(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$	Dispatch	Nutritional	Shortage	Waste by (kg)		Beneficiaries	Execution time (s)	
	(kg)	gap	(kg)	Expiration	Degradation	served	DP	Multi-obj
(0,0,0,1)	21 066.05	26 083 329	338 881.9	18 133.23	0	95	0.511	2.263
(0,0,8,0,0,2)	22 950.29	23 061 264	236 997.7	15 851.7	0	87	0.495	2.255
(0,0,8,0,1,0,1)	22 953.29	24 332 318	236 994.7	15 848.7	0	62	0.503	2.418
(0,0,0,5,0,5)	22 812.2	24 175 819	235 756.7	18 547.7	0	65	0.562	2.738
(0,0,9,0,0,1)	22 953.29	22 533 685	236 994.7	15 842.7	0	92	0.517	2.256
(0,0,1,0)	28 430.63	26 898 808	228 830.4	13 480.0	4 831.22	46	0.495	2.684
(0,0,1,0,9,0)	29 075.11	27 656 275	228 677.9	11 663.2	18 559.54	37	0.508	2.717
(0,0,7,0,3,0)	28 723.36	33 321 413	231 224.6	11 394.2	18 266.04	61	0.506	2.647
(0,1,0,0)	28 109.78	24 551 134	231 838.2	12 007.9	10 031.37	61	0.504	2.119
(0,1,0,0,9)	21 339.78	4 902 220	338 608.2	17 874.2	0	67	0.509	4.276
(0,1,0,1,0,6,0,2)	22 214.25	4 177 094	236 354.7	17 762.7	72.39	59	0.490	6.030
(0,2,0,7,0,1,0)	27 068.35	942 411.7	232 879.6	13 830.0	14 492.73	67	0.509	7.356
(0,3,0,0,0,7)	21 339.78	4 902 220	338 608.2	17 853.9	0	74	0.506	4.409
(0,3,0,0,2,0,5)	22 214.25	4 177 094	236 354.7	17 768.7	72.39	60	0.527	5.346
(0,3,0,1,0,3,0,3)	25 227.36	2 993 325	234 720.6	15 228.6	309	61	0.507	5.527
(0,4,0,1,0,4,0,1)	25 729.46	2 398 119	234 218.5	14 726.5	652.11	59	0.499	5.367
(0,4,0,0,6,0)	27 068.35	942 411.7 325	232 879.6	13 842.0	9 923.45	67	0.503	5.500
(0,4,0,2,0,3,0,1)	25 729.46	2 398 119 325	234 218.5	14 726.5	652.11	59	0.535	5.323
(0,5,0,0,5,0)	27 068.35	942 411.7	232 879.6	13 830.0	11 273.48	66	0.542	5.938
(0,5,0,1,0,0,4)	25 227.36	2 993 325 325	234 720.6	15 228.6	309	71	0.511	4.445
(0,6,0,1,0,2,0,1)	25 803.95	2 374 456	234 144.1	14 622.3	681.90	59	0.510	5.202
(0,6,0,1,0,3,0)	27 068.35	942 411.7	232 879.6	13 830.0	10 234.97	67	0.509	6.069
(0,7,0,3,0,0)	27 068.35	942 411.7	232 879.6	13 830.0	9 271.97	71	0.496	5.868
(0,8,0,2,0,0)	27 068.35	942 411.7	232 879.6	13 830.0	9 271.97	67	0.502	5.044
(1,0,0,0)	27 068.35	942 411.7	232 879.6	13 848.0	9 702.53	68	0.529	5.014

Table 6
Dispatch and waste variation.

Volunteers variation		Dispatch		Waste expired		Waste degraded	
N	Work-hours/week	kg	Variation (%)	kg	Variation (%)	kg	Variation (%)
-1	-40	25 729.46	-5.8%	16 209.54	10.1%	935.13	43.40%
0	0	24 246.44	-	14 726.52	-	652.11	-
1	40	26 894.63	4.5%	13 924.35	-5.4%	385.44	-40.9%
2	80	28 522.72	10.9%	12 296.26	-16.5%	309.00	-52.6%
3	120	29 356.71	14.1%	11 773.27	-20.1%	309.00	-52.6%
4	160	30 270.34	17.6%	10 859.65	-26.3%	286.71	-56.0%
5	200	30 537.87	18.7%	10 592.11	-28.1%	152.21	-76.7%
6	240	30 558.73	18.8%	10 334.63	-29.8%	0.00	-100.0%
7	280	32 478.97	26.2%	8 210.24	-44.2%	0.00	-100.0%
8	320	34 033.71	32.3%	6 784.86	-53.9%	0.00	-100.0%
9	360	34 496.22	34.1%	6 484.76	-56.0%	0.00	-100.0%

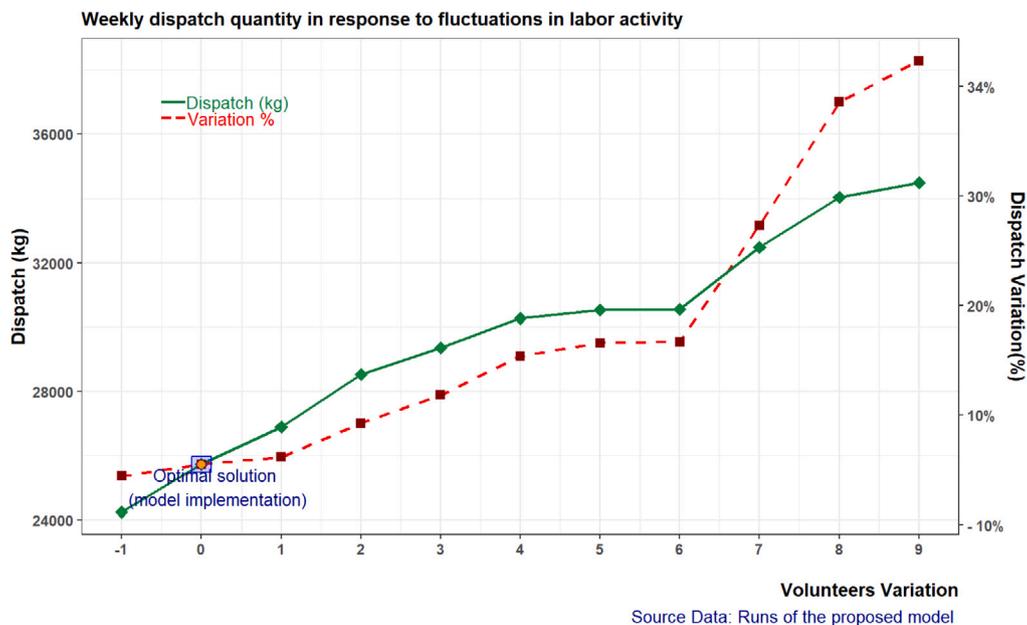


Fig. 3. Dispatch sensitivity curve.

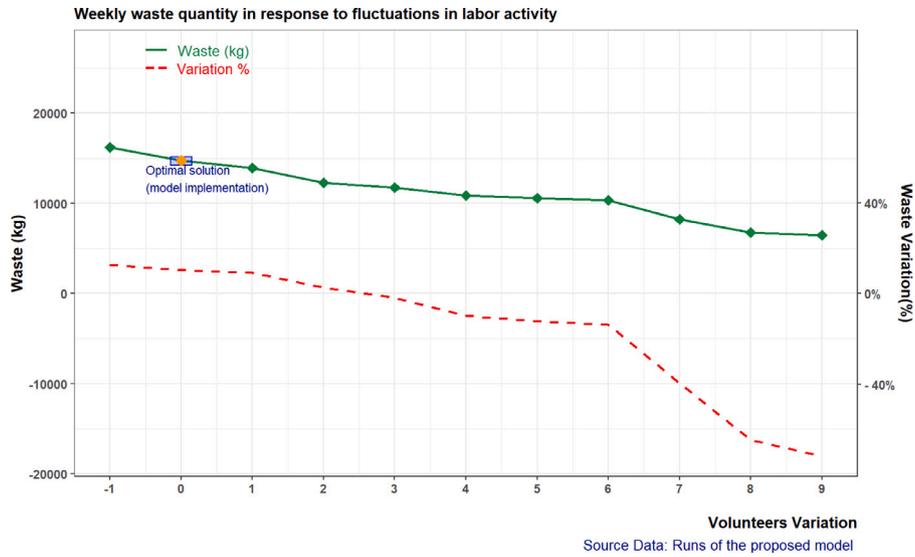


Fig. 4. Waste sensitivity curve.

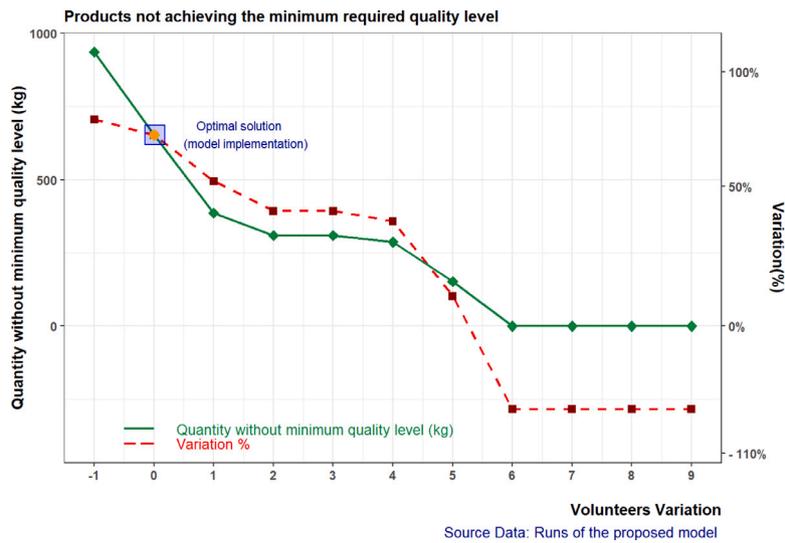


Fig. 5. Sensitivity curve for products that do not meet minimum quality requirements.

Table 7

Results of the computational experiment for variations in the planning horizon T of the proposed model.

T	Dispatch (kg)	Nutritional gap	Shortage (kg)	Waste by (kg)		Beneficiaries served	Execution time (s)	
				Expiration	Degradation		Multi-obj	DP
6	25 729.46	2 398 118.96	234 218.54	14 726.52	652.11	58	5.36	0.63
7	29 913.98	840 994.81	235 271.51	13 894.22	604.88	59	4.89	0.63
8	41 581.34	597 826.17	239 187.76	34 091.29	818.38	47	37.55	1.21
9	43 406.84	1 015 110.18	239 397.99	35 426.79	1 480.16	42	33.25	1.27
10	48 283.31	2 859 395.23	239 654.83	38 723.63	2 017.97	51	42.95	1.42
11	45 757.58	2 045 950.82	239 523.31	37 174.01	1 605.38	47	37.96	1.39
12	31 200.35	17 979.74	237 246.42	17 152.00	0.00	60	7.56	0.72
13	31 568.96	8 282.58	237 190.27	18 957.05	0.00	65	10.23	0.73
14	36 129.47	0.00	238 347.67	20 103.64	0.00	65	18.98	0.84
15	51 723.01	5 246 041.34	239 654.83	40 580.13	2 043.00	50	45.88	1.49
16	37 302.35	4 254.03	237 604.66	21 377.40	0.00	61	15.55	0.89
17	42 520.85	28 374.42	237 348.28	21 762.86	0.00	57	18.37	0.95
19	42 012.72	92 451.21	238 619.84	26 043.63	0.00	60	34.01	1.02
20	42 430.00	310 487.05	237 808.48	29 972.15	0.00	55	32.38	1.09

Table 8
FEFO policy illustration.

		Arrival date					
		Su	Mo	Tu	We	Th	Fr
Dispatch day	Mo	620					
	Tu						
	We						
	Th				294		
	Fr			180			

robustness of the current plan in the face of potential cost fluctuations of available volunteers. The fluctuation in the number of volunteers also influences the quantity of products deemed unsuitable for dispatch to beneficiaries due to their failure to meet the minimum quality standards. As depicted in Fig. 5, a reduction of one volunteer leads to a 43.40% increase in the volume of products failing to meet the requisite quality criteria, necessitating their categorization as degraded and subsequent processing

In summary, sensitivity analysis for our MILP model provides decision-makers with valuable insights into the flexibility and resilience of our optimization solution. It helps us anticipate and adapt to changes in the number of volunteers, ensuring that warehouse operations remain controlled in a dynamic environment. This ability to assess the impact of potential changes is fundamental for informed decision-making and risk management. In the present case study, the available inventory was consistently lower than the minimum demand from the beneficiaries. Therefore, the problem outlined in Section 4.5 simply involved reallocating the products to beneficiaries based on their score.

Table 7 displays results for some values of T , starting from $T = 6$. Parameters were randomly generated for cases where T was greater than or equal to 7. The final two columns indicate the execution time in seconds of the main problem and its subproblems. Finally, Table 8 illustrates how the coefficients of f_2 handle the FEFO (First Expired, First Out) policy for a specific product. The columns represent the arrival day, and the rows correspond to the day the product was dispatched. The cells in color represent the days the product has before its expiration, in other words, the days it can be dispatched. For example, 180 kg of a product arrives on Tuesday and has three days before expiration, so it can be dispatched from Wednesday to Friday inclusive. The goal is to maximize the quantity to dispatch, prioritizing items with a shorter shelf life. In Table 8, we can see that the 180 kilograms that arrived on Tuesday have three days of shelf life, so in the objective function for these 180 kilograms and for the 294 kilograms that arrived on Tuesday and Wednesday, the coefficients are $\frac{1}{3}$ and $\frac{1}{2}$, respectively. When minimizing $-f_2$ or maximizing f_2 , the optimization algorithm will prioritize the variable with the highest coefficient, meaning the one with the shortest remaining shelf life before expiration.

6. Conclusions and future research

We have introduced a multi-objective, multi-product, multi-period perishable product allocation model for a food bank operating under the First-Expiry-First-Out (FEFO) warehouse policy. The primary objective of this model is to determine the optimal allocation of products, considering the nutritional requirements of the beneficiaries, constraints on labor availability, and addressing scenarios of insufficient inventory. To incorporate the FEFO policy, we created appropriate parameter sets and introduced a prioritization factor into one of the objective functions.

Our model simultaneously aims to maximize the quantity of products dispatched while minimizing the nutritional gap between what is dispatched and the beneficiaries' requirements. Given that the number of beneficiaries and product quantities is not significantly large, we employed the CPLEX solver to obtain solutions for the multi-objective problem.

Notably, our numerical experiments demonstrated how implementing this model can serve as a valuable planning tool, enabling timely decisions to better satisfy the beneficiaries.

This work leads to many opportunities for future research from both modeling and solution techniques perspectives. One potential extension is to represent the dispatch units by product bundles to facilitate handling and eliminate the need for repetitive weighing within the warehouse. While this could practically save time during the picking process, it would introduce additional integer constraints, increasing the complexity of obtaining an optimal solution. The feasible region can be viewed as the intersection of T independent set of variables linked by constraints involving variables from different independent sets. This structural characteristic, coupled with the integer nature of the problem, makes it suitable for the Branch and Price optimization algorithm.

In the context of our current case study, we considered the arrivals of products and their days remaining until expiration as known parameters. However, if we were to account for uncertainty in these parameters, we would be dealing with a multistage stochastic integer problem. The Branch and Price algorithm is a heuristic based on the Branch and Bound method, but at each node, it solves the problem's relaxation using the column generation algorithm. We could design a heuristic to efficiently generate initial columns in this case. It would be worthwhile to explore interactions between multiple warehouses and address waste control in a network of food banks. Lastly, f_1 objective function may require a deeper understanding of the different nutrients involved. The total of nutritional gaps was scaled, but further analysis from experts in the field of nutrition is required as f_1 is indeed a multi-objective function.

CRedit authorship contribution statement

Carlos Aníbal Suárez: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Conceptualization. **Walter A. Guano:** Writing – review & editing, Validation, Software, Investigation, Data curation. **Cinthia C. Pérez:** Writing – review & editing, Validation, Investigation, Conceptualization. **Heydi Roa-López:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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