



Optimal allocation of near-expiry food in a retailer-foodbank supply network with economic and environmental considerations: An aggregator's perspective

Jasashwi Mandal^{a,*}, Rony Mitra^a, Vishal Kumar Gupta^b, Nachiappan Subramanian^c, Yaşanur Kayikci^d, Manoj Kumar Tiwari^{b,e}

^a Department of Mathematics, Indian Institute of Technology Kharagpur, Kharagpur, 721 302, West Bengal, India

^b Department of Industrial and Systems Engineering, Indian Institute of Technology Kharagpur, Kharagpur, 721 302, West Bengal, India

^c University of Sussex Business School, University of Sussex, Brighton, United Kingdom

^d Department of Industrial Engineering, Turkish-German University, Istanbul, Turkey

^e National Institute of Industrial Engineering, Mumbai, India

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ABSTRACT

Wastage of perishable food products is a severe concern to society and needs to be addressed to ensure food security for all. Moreover, the food waste when sent to landfills, decomposes to produce greenhouse gases like methane and carbon dioxide. The emergence of food banks and aggregators has abated the problem of food wastage to a certain extent. An aggregator, which connects the retailers to the food banks, plays a critical role in ensuring that the food reaches the food banks on time. However, to ensure food security and reduce wastage of food, it is essential that food aggregators remain profitable. The aggregator has to determine the number of heterogeneous vehicles to hire from the market and allocate them their route on a daily basis depending on donations committed by the retailers and also take into account potential environmental impact from the decomposition of food waste and carbon emitted from hired vehicles. Hence, we propose decision support for aggregators, using data from an aggregator based in Turkey, which can help in reducing food wastage by allocating the donated food items from retailers to food banks while maximizing the profitability of the aggregator and minimizing the environmental impact. We have also analyzed how the availability of different types of vehicles can impact the aggregator's profit. Furthermore, the effect of various model parameters such as transportation cost, and percentage of retailers' gain paid to the aggregator on the total profit along with the impact of distances on types of vehicles hired is also analyzed. We have compared two strategies that the aggregator could possibly employ and generate managerial insights.

1. Introduction

Limited availability and accessibility to safe and nutritious food for individuals are known as food insecurity. To provide food assistance to the needy people, government-funded programs, private sector corporations, manufacturers and retailers provide food to food banks, which operate as non-governmental organizations (NGOs). Food banks are operated as collection and distribution centers of donated food. They help in collecting, inspecting, storing, and distributing food products to charitable agencies. The notion of food banks originated in the USA in the late 1960s and was introduced in Turkey by the government in an

omnibus bill in 2004. 10 foundations and 20 associations were authorized to engage in food banking by the Interior Ministry (Görmüş, 2019). The concept of food banks has spread fast in the following decade and it claims to supply food for thousands of families suffering from food insecurity as studied by Koc (2014).

Transporting large quantities of near expiry food from retailers to food banks poses logistical challenges in terms of delivering them on time so that the food can still be consumed, thus providing opportunity for entrepreneurs to act as aggregators. An aggregator connects the retailers who donate food products close to their sell-by date with food banks. Aggregators receive the information about the unsold inventory,

* Corresponding author.

E-mail addresses: jasashwi17_kgp@iitkgp.ac.in (J. Mandal), ronymitra92@iitkgp.ac.in (R. Mitra), vkg03@hotmail.com (V.K. Gupta), N.Subramanian@sussex.ac.uk (N. Subramanian), yaşanur@tau.edu.tr (Y. Kayikci), mkt09@hotmail.com (M.K. Tiwari).

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which usually gets wasted resulting in losses for the retailer. They collect the near expiry food, sort them by the quality and help the retailers to dispose of them. Food that can still be consumed is then transported to the food bank warehouses and is distributed to the needy people for free. For donating the food close to their sell-by date and about to be wasted, retailers are qualified for tax exemption and get a percentage of tax benefits based on the value of food saved. Retailers have to pay the aggregator a certain percentage of their gain. Transportation is also a significant contributor to greenhouse gases (GHGs). The unique business model of the aggregator, which earns revenue from the share of the tax incentives, received by the retailer, and the fact that the aggregator monitors the practices followed at food banks to prioritize allocation and deliveries make them different from traditional third-party logistics service providers.

Turkey is the world's 20th largest emitter of greenhouse gases (GHGs) and shares 0.8% of global GHG emissions by Climate transparency report (2017). In Turkey, the amount of CO₂ equivalent emissions due to transport has reached 220 million tons of CO₂ equivalent (MtCO₂e) in 2015 according to a report by the Carbon Brief Profile: Thyberg and Tonjes (2017). Climate transparency report (2017) says the transport sector in Turkey contributed 16% of GHG emissions in Turkey in 2015. Since logistics operations are significant sources of GHG emissions, an effective design of a retailer-foodbank network is needed which can ensure profitability for the aggregator while lowering the CO₂ emissions. Hence, one key decision for the aggregator is to allocate donated food from retailers to food banks is to deal with conflicting objectives such as maximizing the revenue obtained from the retailers and minimizing the transportation cost, waste disposal cost, amount of carbon-equivalent emissions, and the greenhouse gas emissions. Unlike conventional allocation problems, which needs to consider distances and capacity of warehouses, in the case of food bank logistics, the allocation also needs to consider the quality rating of the food banks by the aggregator based on their past performance in terms of good storage and handling practices. Moreover, due to the perishable nature of some of the food being transported, the products have to be transported at optimal temperature. For a particular percentage of the tax incentive which the retailer would like to share with the aggregator, the aggregator has to minimize its costs and maximize its revenues while ensuring that the products are delivered at the appropriate conditions and the environmental effects are minimized. But, the aggregator has the flexibility of not catering to certain food banks, if they do not have good practices of handling the food products or they are at a long distance away from retailers and other food banks. This also helps the aggregator to keep costs low. If the aggregator wants to maximize its revenues and wants to cater to a larger number of food banks, it has to incur additional costs by hiring additional vehicles.

Optimal allocation of products between suppliers and buyers while minimizing transportation costs and greenhouse gas emissions have been studied by multiple authors (Ali khani et al., 2019; Kannan et al., 2013). But, there is limited literature on the optimal allocation of food to the food banks that includes objectives such as maximizing the profit for the aggregator while considering both the transportation and the environmental costs. As stated by Nair et al. (2017b), routing problems have not received sufficient attention in the case of food rescue operations.

Therefore, the main contributions from this study are as follows: (i) proposing first the kind decision support tool to design an optimal retailer-foodbank network where food aggregators act as an intermediate agent, (ii) developing a mathematical model incorporating economic and environmental dimensions in addition to time windows into the decision-making process of the aggregator, (iii) incorporating deterioration of product in transit based on the distance covered and operational speed of heterogeneous vehicles. We tested the applicability of the model using real-life data from an aggregator based in Turkey.

The remainder of this paper is organized as follows: Section 2 outlines the literature review on sustainability in supply chain network design for food banks or food supply chain management. The problem

description and mathematical formulation of the supply network design problem containing the collection, transport, and delivery phases and the solution approach are presented in Section 3. Applicability of the model and results are discussed in Sections 4 and 5 respectively. The major outcomes of the study and future research directions are spelled out in the concluding section.

2. Literature review

Supply chain network design (SCND) decision has a significant role in optimizing the performance of a supply chain (SC) as it affects the total operational costs in a long run. SCND deals with planning at different levels. Facility location and customer allocation are the strategic level decisions included in the SCND problem. The tactical decision deals with inventory control in facilities and routing decision is the operational decision related to the SCND problem (Zheng et al., 2019). Melo et al. (2009) highlighted the economic concerns such as minimizing cost or maximizing profit in designing a supply chain network. Moreover, environment-related issues are increasingly been considered at the strategic level. Different metrics including GHG emissions during transportation are identified to assess the environmental impact and to measure the performance of sustainable supply chains (Eskandarpour et al., 2015). Such metrics are incorporated by Musavi and Bozorgi-Amiri (2017) in a study where a multi-objective MILP model is solved using NSGA-II to optimize SCND decisions in the perishable food supply chain. The objectives were to optimize the total transportation costs, food quality, freshness during shipping, and total carbon emissions related to transport.

The economic and environmental issues in decision-making processes were considered by Bloemhof-Ruwaard et al. (1995) informing the possibilities of environmental concerns in industrial supply chains. All the three dimensions, economic, environmental and social issues of sustainable supply chain management (SCM) are receiving growing attention in global supply chains (Koberg and Longoni, 2019). Walther et al. (2007) explored how to improve the trade-offs between profitability and environmental concerns in a reverse logistics network using a two-phased heuristic to find pareto-optimal solutions. Sustainability perspectives have also been considered in the food supply chain (Saif and Elhedhli, 2016), who modeled a cold supply chain network design problem minimizing total supply chain cost containing capacity, inventory and transportation costs, and total global warming impact and solved it using a simulation-optimization algorithm. Similarly, an integrated model is developed to determine optimal lot-sizing, quantity of shipping, number of trucks, and number of freezer units minimizing the operational cost and costs due to carbon emissions in a cold supply chain (Hariga et al., 2017). The authors observed that incorporation of carbon emission costs, in terms of carbon tax regulation, may result in a minor increase in the operational cost, but it is less than the savings realized through carbon-related costs. Bottani et al. (2019) analyzed the economic and environmental effects of various reverse logistics scenarios for gathering packaged food waste from retailers and transporting it to a facility for treatment and reprocessing, to divert it from landfill disposal to alternative networks. The economic analysis uses a theoretical model to calculate the optimum number of facilities in the network and the routing of vehicles that will visit retail stores to collect spoiled food, with the overall logistics cost as production. The life cycle evaluation approach is also used to perform an environmental study. The findings indicate that, while gathering the entire amount of wasted food is more costly in terms of transportation costs, it is the more environmentally friendly alternative.

A few studies have addressed the scheduling and routing problem for non-profit organizations in the context of food rescue and distribution. In this domain, Solak et al. (2014) introduced a variant of location-routing problems, stop-and-drop problem (SDRP) containing a central warehouse to store the donated foods and delivery sites where agencies pick up the delivered food. The tactical strategy includes how to choose a set of delivery sites, allocate agencies to these sites, and find

routes for the shipping vehicles. Mohan et al. (2013) optimized the operational decisions in a non-profit supply chain distributing food to the “food insecure” and improved the efficiency of its operations by solving a simulation model. Nair et al. (2018) presented a routing and scheduling problem inspired by the food relief process in Sydney, where the surplus food is rescued from various food providers and distributed to charitable agencies. They developed a linear programming model and also proposed a Tabu Search-based heuristic approach to solve this problem. Davis et al. (2014) determined the transportation schedules for food banks collecting food donations from providers, delivering them to welfare agencies, and incorporating constraints for food safety, fleet capacity, operating workday, and collection frequency. The study also identified satellite locations (named food delivery points (FDP)), where agencies can pick up food rather than going to the food bank warehouses. Later, Rey et al. (2018) proposed a Benders’ decomposition-based cutting-plane algorithm for finding envy-free allocation and cost-effective routes for donated food pick-up and delivery. Bottani et al. (2018) presented a location and routing model with Microsoft Excel to develop a reverse logistics channel for food waste, with a focus on waste created at the retail stores of the food supply chain. The model was applied to the Emilia-Romagna region of Italy. The aim of the application was to arrive at some tentative conclusions about the economic viability of establishing a reverse logistics channel to recover food waste and redirect it to alternative uses rather than landfills. A cold chain route optimization model including carbon emission was developed by Zhang et al. (2019) and solved with an approach Ribonucleic acid computing combined with ant colony optimization. Recently, Leng et al. (2020) designed a cold supply chain green location routing problem to minimize the total transportation costs and vehicle and client waiting time.

A closely related problem of multi-period, multi-product, and multi-echelon food bank supply chain network redesign for the collection and distribution of food donated is recently published by Martins et al. (2019) and motivated by the Portuguese Federation of Food Banks (FPBA). In addition to the strategic decisions to open new food banks, select the storage and transport capacities, and to close existing unnecessary food banks, the model also includes decisions related to transportation of collected and distributed food. To improve the sustainability performance of the FPBA, all three dimensions: economic, environmental, and social are considered in the proposed MILP model. From the aspect of green logistics, Ala-Harja and Helo (2015) listed out performance metrics for different supply chain decisions and their role to form an efficient and sustainable supply chain. Importance of sustainability particularly in the food supply chain is significantly increasing, since apart from the fuel emissions, refrigeration of food items during transport or storage directly affects it. Specifically, a significant amount of electricity is consumed for food refrigeration, and this energy in the supply chain accounts for GHG emission and climate change (Tassou and Lewis.).

The non-profit organizations rescue surplus food from different food providers and redistribute it to the food insecure. However, the quantity of food available to be donated is not fixed and varies with different situations. To address this problem, Brock and Davis (2015) explored four forecasting methods that can estimate the availability of food donations at supermarkets despite uncertain information. When there are uncertainties in supply, recognizing the dynamics of food rescue and estimating food donations have significant importance in food collection and distribution, especially in acquiring an equitable and sustainable food distribution with less operational costs (Nair et al., 2017a). Moreover, food waste in landfills produces a large amount of methane which further causes GHG emission polluting the environment. Adelodun and Choi (2020) have worked on food wastage throughout a supply chain and measured the Green House Gas (GHG) emissions and water footprint associated with the wastage. Between 2007 and 2017, the average wastage of food in Korea was about 16 million tonnes across the supply chain. Mosna et al. (2016) determined the suitability of flour food items

discarded during the distribution process as a raw material for animal feed processing. The study compared the environmental effect of producing new feeds that are partially produced from food waste to conventional animal feed production using the Life Cycle Assessment approach. Overall, this research showed that manufacturing animal feed from food waste is a more environmentally sustainable alternative than producing conventional animal feed, as well as preventing the landfilling of packaged floor food. Hu et al. (2019) examined the trade-offs between food loss and energy consumption along the cold chain considering GHG emissions. Vitale et al. (2018) described an experimental method for collecting packaged food waste from retailers, transporting it to distribution centers, and then shipping it to a facility where the food is sorted from the package. Just a limited amount of packaging material was disposed of in landfills after the sorted foods are sent to recycling in this method. They have also discussed the environmental performance of the proposed method comparing it with the existing process Life Cycle Assessment (LCA) methodology. This paper focuses on the end-of-life (EOL) of packaging products considering various processes (energy recovery, recycling and landfill).

Taking into account the cumulative effect of global supply chains on the climate, the Food and Agriculture Organization of the United Nations (FAO) reports that food loss and waste accounts for about 7% of global GHG emissions. From an environmental and economic perspective, Ahamed et al. (2016) presented a Life cycle assessment of food waste management technologies such as anaerobic digestion and food waste-to-energy biodiesel system. Thyberg and Tonjes (2017) presented the environmental effects of residential waste disposal in the United States to see whether a suburban municipality could benefit from separate food waste recovery and treatment. Cakar et al. (2020) measured the embedded carbon, water, and energy footprints in the food supply chain in Turkey, and evaluated the environmental effect of food waste on climatic, water, and energy supplies. They estimated that food waste in Turkey embodied 23.7 Mt of CO₂-eq, 6.2×10^9 m³ of water, and 13.5×10^4 TJ of energy. Similarly, Damiani et al. (2021) highlighted and analyzed the environmental consequences of food waste during the food production and consumption cycle.

Even though food distribution and logistics have drawn much attention in the literature, specifically the network design and allocation problem considering three levels such as retailer, aggregator, and food bank network have received limited attention. None of the previous studies considered the food allocation problem to the food bank from the point of view of the aggregator. To the best of our knowledge, the significant contributions of this paper are as follows: (i) The problem of allocating and delivering food from retailer to food bank where food aggregators act as an intermediate agent is addressed for the first time in the literature related to food rescue and distribution. (ii) A strategic multi-objective decision model which maximizes profit for the aggregator and minimizes the environmental impact while delivering the food in the optimal quality and within time windows is formulated here. (iii) Our model can be used to determine the optimal number of heterogeneous vehicles to be hired by the aggregator to fulfill the demand at various food banks based on their rank to incentivize better-performing food banks. Thus, the proposed model introduces a multi-echelon supply chain network design problem with fixed time windows in the perishable food supply chain context. The computational study performed on the problem instances is based on the real data collected from an aggregator in Turkey. The study generates additional insights on the impact of tax incentives for the retailer, the percentage of the tax incentives shared by the retailer with the aggregator, and the transportation costs for the different types of vehicles.

3. Retailer-foodbank supply network model

In this section, the retailer-food bank supply network is described in detail and a multi-period, multi-echelon, multi-product strategic MIP model formulation is discussed below.

3.1. Problem definition

The food supply network includes three different types of entities: retailers as donors, aggregators, and food banks. Here, selected food products are donated by the retailers. Typically, the donated food products, approaching their sell-by date, are not sale-worthy, but they are still edible. The retailers require the products to be picked up and delivered to the food banks. The aggregator has visibility about the volume of products to be donated by the retailers and uses hired trucks to pick up the food products from the retailers and deliver those to the food banks. In this problem setting, the food banks are not allocated to the retailers. Instead, the aggregators have to decide which food banks to fulfill based on their performance in terms of having good practices of proper storage, maintenance, and equitable distribution of the foods to the food insecure people.

Each food bank operates a warehouse to store the food donations. The donated food products may be dry products (e.g., packaged foods), fresh food (e.g., fruits and vegetables), and frozen products (e.g., fish and meat). Aggregator needs to allocate the donated food from retailers to food banks based on the distance between them as well as a rating of food banks. Hence, the decisions to be taken are allocating food banks to retailers and the amount of food products to be donated to each food bank over a multi-period planning horizon and considering various parameters (e.g., food supply, demand levels, time windows, and the emissions). Fig. 1 portrays a schematic representation of the retailer-food bank supply network with the aggregator as an intermediary.

Furthermore, it is assumed that the aggregator can hire different types of vehicles based on their availability and their ability to transport a given type of product. A vehicle may be refrigerated or may not be refrigerated. The vehicle can be fast or slow; it can be large or small. That implies there is no limit on the type of vehicle that the aggregator can hire. However, not all food items can be shipped by all kinds of vehicles. For example, a refrigerated vehicle can carry a product to a larger distance with little or no degradation on the way. In contrast, a pickup truck cannot maintain the freshness of highly perishable products like meat.

The complexity of this problem increases further because of an operational requirement imposed by the aggregator. The demand of the food banks must be fulfilled based on their rank to incentivize better-performing food banks. It has to be noted that there is a gap in demand and supply and not all the demand at the food banks can be

fulfilled with the donated food items. This imposes a unique challenge in terms of mathematical formulation that has not been addressed previously.

3.2. Model formulation

In this section, we formulate the mathematical model for the proposed problem. We have delineated all the sets, indices, model parameters and decision variables. Afterwards, the economic and environmental objective functions and corresponding constraints are presented.

3.2.1. Model parameters

The notations for sets, indices and parameters are introduced hereafter.

Sets:

R	Set of retailers
B	Set of foodbanks
P	Set of products
T	Set of time periods
V	Set of all vehicle types

Indices:

r	Index of retailers
b	Index of food banks
p	Index of product
t	Index of time period
v	Index for vehicle type
α	Index for rank foodbank

Parameters:

I	Tax rebate
γ	Percentage of tax rebate the retailer shares with the aggregator
K_p	Price of product p per unit for a consumer in the market
FR_{rv}	Fixed cost for picking up products from any of the retailer r on vehicle v
FB_{bv}	Fixed cost to move the products into a food bank b from vehicle v
PR_{rv}	Penalty for time windows violation for retailer r
PB_{bv}	Penalty for time windows violation for food bank b
TW_{rv}^R	1, if retailer r allows vehicle of type v to be picked up at time period t , otherwise
TW_{bv}^B	1, if food bank b allows vehicle of type v to be delivered at time period t , otherwise
TC_v	Fixed Transportation cost per unit distance for vehicle type v
$dist_{rb}$	Distance between retailer r and food bank b
$speed_{rbv}$	Average speed of vehicles v from retailer r to food bank b
Q_p	Total quantity of product p donated by retailer r
S_{pv}	Percentage of product p that survives after traveling on vehicle v for 1 hour
q_{rbpv}	Percentage of quantity of product p donated by retailer r that will remain consumable if sent to food bank b on vehicle v
D_{bp}	Max acceptable quantity of consumable product p at food bank b
d_{bp}	Min acceptable quantity of consumable product p at food bank b
GWP_{HFC}	Global warming potential index of HFCs
$eHFC_v$	Average HFC gas leakage from vehicle v per unit distance traveled
eCO_2F_v	Average CO_2 emissions from the vehicle v per unit distance traveled
eCO_2D_p	Average CO_2 emission from decomposition of one unit of product p
w_p	Waste disposal cost for one-unit of product p
β	Cost per unit equivalent CO_2 emissions
M	A large positive value
n	Total number of food banks
$M_{max,v}$	Maximum weight carrying capacity of the vehicle
$V_{max,v}$	Maximum space available in the vehicle for the product
v_p	Volume of a unit of product p
m_p	Mass of a unit of product p
O_{pv}	

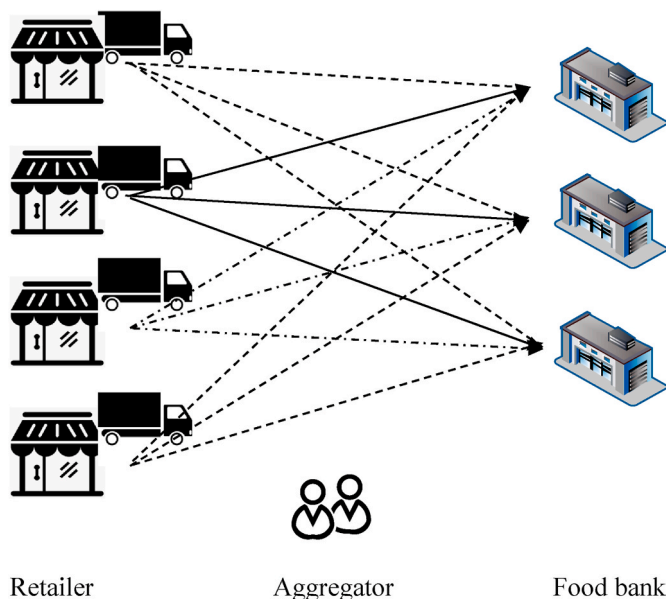


Fig. 1. Retailer-foodbank supply network.

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	1, if product p can be transported on vehicle v , if product p cannot be transported on vehicle v
R_{bp}	Priority of food bank b for product p (1, 2, 3, ..., n)
f_{ap}	Order of food bank according to their priority for product p
N_{rv}	Number of vehicles of type v made available at time t at retailer r

Decision variables:

y_{rbtpv}	Quantity of product p transporting from retailer r to food bank b at time period t on vehicle v
T_{rv}^R	Binary variable whether the pickup is done from retailer r at time period t on vehicle v
T_{bv}^B	Binary variable if the delivery is done to the food bank at time period t using vehicle v
X_{bp}	1, if the demand for product p at food bank b is fulfilled 0, otherwise
Y_{rbtv}	Binary variable, 1 if there is a transfer of goods from retailer r to food bank b at time t on vehicle type v

3.2.2. Profit maximization of the aggregator

The objective function (1) is designed to maximize the profit of the aggregator and comprises seven components. The first term in the objective function shown in equation (1) denotes the total profit of the aggregator which is a certain percentage (γ %) of the retailers' revenue achieved from tax exemption due to food donation. It includes the total fixed cost for picking up the food at the retailers (the second component) and penalty cost for violating the fixed time window for picking up foods at the retailers (the third component). The latter cost represents the fixed

$$\begin{aligned} \text{Max } z_1 = & (\gamma/100) * I \sum_{r \in R} \sum_{b \in B} \sum_{t \in T} \sum_{p \in P} \sum_{v \in V} K_p y_{rbtpv} q_{rbtpv} - \sum_{r \in R} \sum_{t \in T} \sum_{v \in V} (FR_{rv} T_{rv}^R) - \sum_{r \in R} \sum_{t \in T} \sum_{v \in V} PR_{rv} (TW_{rv}^R - T_{rv}^R)^2 \\ & - \sum_{b \in B} \sum_{t \in T} \sum_{v \in V} (FB_{bv} T_{bv}^B) - \sum_{b \in B} \sum_{t \in T} \sum_{v \in V} PB_{bv} (TW_{bv}^B - T_{bv}^B)^2 - \sum_{r \in R} \sum_{b \in B} \sum_{t \in T} \sum_{v \in V} TC_{v, dist_{rb}} Y_{rbtv} \\ & - \sum_{p \in P} \left(w_p \sum_{r \in R} \left(Q_{rp} - \sum_{b \in B} \sum_{t \in T} \sum_{v \in V} (y_{rbtpv} q_{rbtpv}) \right) \right) \end{aligned} \quad (1)$$

cost of delivering products to food bank warehouses. The fifth term denotes the time window violation penalty cost for food arrival at food banks. The sixth component is the cost for transporting the food products from retailer to food banks with the help of hired trucks. Finally, the last term is total waste disposal cost of the discarded food. Since the food products are perishable, wasted food has to be disposed of at a cost.

3.2.3. Environmental objective

The environmental objective function shown in equation (2) minimizes the total cost for CO₂-equivalent amount of GHG emissions during food delivery by the hired trucks between retailers and food banks (the first term) and cost for CO₂ emissions due to waste disposal of unusable food at retailers (second term). The overall global warming impact of both emitted gases CO₂ and HFC is quantified according to the equivalence principle of the unit of HFC emission and GWP_{HFC} units of CO₂.

$$\begin{aligned} \text{Min } z_2 = & \sum_{r \in R} \sum_{b \in B} \sum_{t \in T} \sum_{v \in V} (GWP_{HFC} \cdot eHFC_v + eCO_2 F_v) \beta dist_{rb} Y_{rbtv} \\ & + \sum_{p \in P} \left(eCO_2 D_p \sum_{r \in R} \left(Q_{rp} - \sum_{b \in B} \sum_{t \in T} \sum_{v \in V} (y_{rbtpv} q_{rbtpv}) \right) \beta \right) \end{aligned} \quad (2)$$

Therefore, to maximize the total profit of aggregator and to minimize the total cost for CO₂-equivalent emissions, the main objective function is to maximize (total profit of the aggregator - total cost for CO₂ equivalent emissions) and formulated as:

$$\text{Max } (z_1 - z_2) \quad (3)$$

Subject to

$$\sum_{b \in B} \sum_{t \in T} \sum_{v \in V} y_{rbtpv} \leq Q_{rp} \quad \forall r, p \quad (4)$$

$$y_{rbtpv} \geq 0 \quad \forall r, b, t, p, v \quad (5)$$

The constraint shown in equation (4) enforces that the total quantity of products being transported to the food banks from retailer r should not exceed the available amount at retailer r in each time period t . It must be ensured that food being transported to the food bank must have the required quality level at the retailer in each time t . Constraints (5) imply the non-negativity of y_{rbtpv} .

$$\sum_r \sum_b \sum_t y_{rbtpv} \leq M \cdot O_{pv} \quad \forall p, v \quad (6)$$

The constraint shown in equation (6) ensure that the food will be donated depending upon the compatibility in transporting the food by a specific type of vehicle v . For example, if product p can be carried by vehicle v then $O_{pv} = 1$ and y_{rbtpv} can have a positive value for the product p and vehicle v . Alternatively if $O_{pv} = 0$, product p will not be transferred using vehicle v .

$$X_{bp} \geq X_{b'p} \mid b = f_{a-1p}, b' = f_{ap} \quad \forall a \in (2 \dots B), p \quad (7)$$

Constraint shown in equation (7) makes sure that food will be donated to the food banks according to their rank based on the past performance. This is a business rule that needs to be introduced to ensure that better performing food banks are given priority over the poor performing ones while allocating the donated food.

$$\sum_{r \in R} \sum_{t \in T} \sum_{v \in V} (y_{rbtpv} q_{rbtpv}) \leq D_{bp} * X_{bp} \quad \forall b, p \quad (8)$$

$$\sum_{r \in R} \sum_{t \in T} \sum_{v \in V} (y_{rbtpv} q_{rbtpv}) \geq d_{bp} * X_{bp} \quad \forall b, p \quad (9)$$

Constraints shown in equations (8) and (9) specify that if $X_{bp} = 1$ for food bank b and product p , the quantity of donated food should lie between minimum and maximum acceptable quantity of food wherein $y_{rbtpv} q_{rbtpv}$ represents the quantity of product p donated by retailer r that will remain consumable if sent to food bank b on vehicle v .

$$\sum_b Y_{rbtv} \leq M \cdot T_{rv}^R \quad \forall r, t, v \quad (10)$$

$$\sum_r Y_{rbtv} \leq M \cdot T_{bv}^B \quad \forall b, t, v \quad (11)$$

Constraints shown in equations (10) and (11) indicate that vehicle of type v can only go from retailer r to food bank b at a given time t if pickup and delivery is available at retailers and food banks respectively at that time period.

$$\sum_b Y_{rbtv} = N_{rv} \quad \forall r, t, v \quad (12)$$

Constraint shown in equation (12) ensures that there is a transfer of goods from retailer r to food bank b at time t on vehicle type v only when the vehicle is made available by aggregator at retailer r at time t .

$$\sum_r \sum_p y_{rbtpv} \leq M \sum_r Y_{rtv} \quad \forall b, t, v \quad (13)$$

$$\sum_b \sum_p y_{rbtpv} \leq M \sum_b Y_{rtv} \quad \forall r, t, v \quad (14)$$

Constraints shown in equations (13) and (14) allow a positive value for y_{rbtpv} only when vehicle v transports food from retailer r to food bank b at time t .

$$\sum_p v_p y_{rbtpv} \leq V_{\max, v} \quad \forall r, b, t \quad (15)$$

$$\sum_p m_p y_{rbtpv} \leq M_{\max, v} \quad \forall r, b, t, v \quad (16)$$

Constraints shown in equations (15) and (16) ensure that the volume and weight carrying capacity constraints of the vehicle type v are not violated.

3.3. Solution approach

To solve the maximization problem shown in equation (3) that is subjected to the constraints shown in equations 4–16, the number of hired vehicles is considered as an input parameter. But first, the optimal number of vehicles to be hired has to be determined. To find the number of vehicles to be hired, constraints (12.a) need to be satisfied instead of constraints shown in equation (12). In constraints (12.a), N_{rtv} is considered as a decision variable.

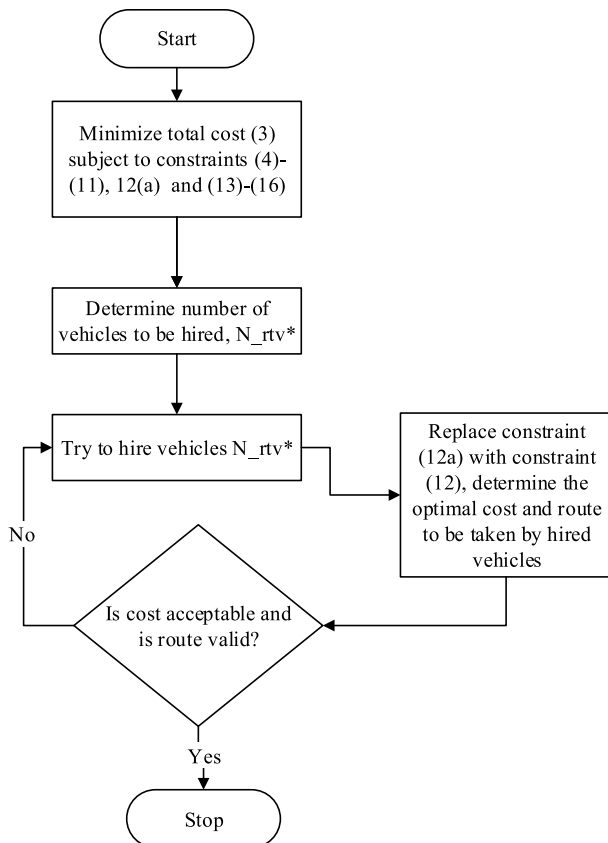


Fig. 2. Flowchart of the solution approach.

$$\sum_b Y_{rtv} \leq N_{rtv} \quad \forall r, t, v \quad (12a)$$

It is assumed that the aggregator knows exactly how much edibles will be donated by retailers on a given day (assume they have a proper channel of communication). Once the aggregator knows this information, he feeds the data into the optimizer to know the optimal number of trucks to hire on a given day. Once the optimal number and type of truck is known the aggregator tries to hire those trucks from the spot market. However, it is not always possible to hire the optimal number of trucks on a day to day basis. When the number of trucks hired is not optimal, the maximization problem (Eqs. (3)–(16)) must be solved using CPLEX. The aggregator can use the formulation to check if a slightly different number of trucks gives a feasible route from retailer to the food bank. Fig. 2 presents a flowchart that illustrates the solution approach.

4. Case study

In this section, the modeling approach is applied in a real-life case study of a retailer-foodbank supply network in Turkey. The network consists of eighteen retailers (R_1 to R_{18}) and nine food banks (F_1 to F_9). The aggregator helps these retailers to donate the food products close to their sell-by date. Aggregator picks up the near expiry food from the retailers R_1 to R_{18} and transports to the food banks F_1 to F_9 by hiring different types of vehicles from the spot market. The food products included in our analysis (P_1 to P_{11}) are Apple, Banana, Tomato, Cucumber, Pumpkin, Carrot, Grape, Beans, Potato, Onion, and Milk, respectively. The prices of the products (in TRY/kg) are presented in Table 1. For food delivery to the food bank warehouses, aggregators use cold chain transport facilities to diminish the wastage of perishable food such as vegetables, fruits, meat, milk, and dairy products. Some products must be transported using refrigerated trucks, for example, meat, milk, or dairy products. Fruits such as apples, grapes need to be refrigerated at 1–4 °C. But vegetables like potato, pumpkin, and tomato do not need to be transported in a refrigerated truck. This necessitates the use of both refrigerated and non-refrigerated trucks.

Vehicles hired by the aggregator differ in capacity and equipment. The food products are transported by mainly three types of vehicles: V_1 (refrigerated or reefer mini truck); V_2 (non-refrigerated medium capacity truck) and V_3 (non-refrigerated large capacity truck). For refrigeration, reefer trucks consume huge energy that is associated with high carbon dioxide (CO_2) emissions. Furthermore, refrigerated trucks use large amounts of Hydrofluorocarbon (HFC) gases having high global warming potential (GWP). Also, HFC gases have a very long lifespan in the atmosphere. Thus, an important element of the global warming impact is the regular and catastrophic HFC gas leakage from the cold supply chain. Average HFC gas leakage from reefer vehicles is 7.5×10^{-7} kg per km. Average CO_2 emissions from the truck type V_1 , V_2 and V_3 are respectively 0.661, 0.661 and 0.751 kg per km. When the food quality drops down the minimum quality level, the products are disposed of at a cost of 0.33 TRY per kg. While disposing of the wasted food, average CO_2 emissions from the decomposition of one kg of product are 3.5 kg. Cost per kg equivalent CO_2 emissions is estimated to be about 0.12 TRY.

The quality of the near expiry food products at the retailers is close to the minimum quality level needed for the food to be consumable after delivery at food banks. The food products are first sorted according to their quality. The spoiled products exceeding their expiration date must be discarded at the retailers. While transporting the sorted food products to the food banks, their quality is influenced by the temperature maintained in the trucks hired by the aggregator. Quality deterioration during transportation is different for each food product depending upon the vehicle temperature. For example, the shelf life of bananas is about 12 days if it is stored at temperature 13–16 °C, shelf life of carrots is near about 28 days while storing at temperature 0.5–2 °C and milk is consumable for 48 h if stored at temperature 1–4 °C. This study assumes

Table 1

Price of donated products in TRY per kg.

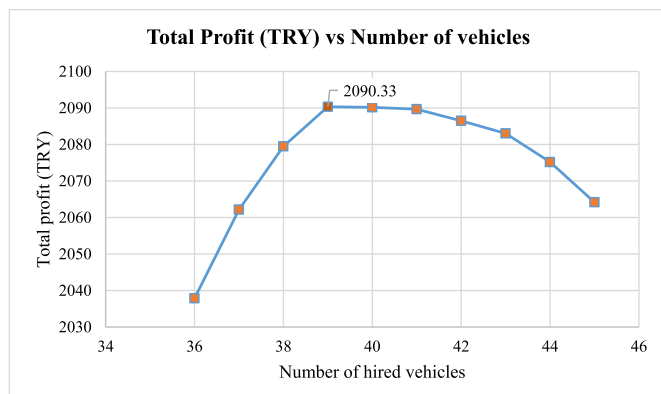
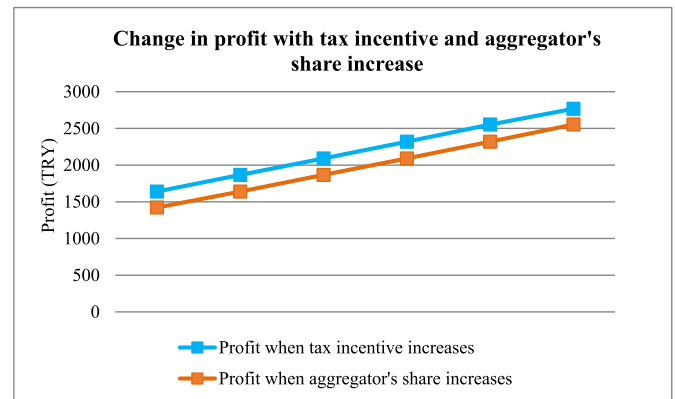
Product	Apple	Banana	Tomato	Cucumber	Pumpkin	Carrot	Grape	Beans	Potato	Onion	Milk
Price (TRY/kg)	4.78	10.8	5.39	1.6	3.94	1.14	3.02	3.14	4.11	4.4	4.16

that a fixed percentage of quantity of each product survives after traveling for 1 h depending upon the temperature of the vehicle (Kitinoja, 2013). In this study, the deterioration rate was adopted from Kitinoja (2014). It is considered that if meat is transported in V_1 type of truck, 95 percent survives after 1 h; similarly, if it is transported in V_2 or V_3 type of truck, 50 percent of the total quantity survives. If milk packets are transported in V_1 type of truck, 97 percent survives after 1 h; similarly, if it is transported in V_2 or V_3 type of truck, 80 or 75 percent of the total quantity survives. Since chilling injury is a disorder for bananas, flesh of the banana goes mushy. They bruise readily, spoil faster and result in an insipid taste when transported in a very high reefer mode. Thus if banana is transported in V_1 type of truck, 80 percent survives after 1 h; similarly, if it is transported in V_2 or V_3 type of truck, 96 and 90 percent of the total quantity survives respectively. Survival rates of vegetables like potato, onion, carrot and cucumber are close to each other in three types of vehicles (about 91–100 percent). This study decides the type of vehicle in which each product will be delivered to minimize the total cold chain cost.

Retailers are qualified for tax exemption for donating the food to the food banks and getting 20 percent of the goods' total cost as a tax rebate. Also, retailers have to pay 20 percent of their gain to the aggregator for delivering the food to the food banks. There is a fixed transportation cost per unit distance for each vehicle charged by the logistic service provider. It is estimated to be 0.06, 0.04, and 0.03 TRY per km for vehicle type V_1 , V_2 and V_3 respectively. The data presented here is closely related to our research contribution, i.e., modeling a retailer-foodbank supply network while taking into account food quality degradation at different temperature levels and CO₂-equivalent emissions in cold supply chains. The full instance data are similar to the data required for standard supply chain models and are not provided here due to lack of space.

5. Results and discussion

The optimization model with the data set presented in the above case study is solved using CPLEX Optimization Studio 12.9. The network results in a problem instance with twenty-six thousand constraints and twenty-three thousand variables (around twenty-one thousand integer variables). As presented in Fig. 2 of section 3, the optimal number of hired vehicles is to be determined first. Solving the model when the number of hired vehicles is considered as a decision variable, the total number of trucks required to transport the donated food at a minimum

**Fig. 3.** Total profit of the aggregator for hiring different numbers of trucks.**Fig. 4.** Total profit of the aggregator for different values of I and γ .

cost is obtained. Fig. 3 presents the aggregator's total profit when the number of hired trucks is between 35 and 45. It can be noticed that when 36 trucks are hired, the profit is low and gets highest when 39 trucks are hired. For hiring greater than 39 trucks, the aggregator's profit continuously decreases in this domain. Fig. 4 represents the variation in aggregator's total profit for different values of the percentage gain of retailers paid to aggregator (orange line) and variation in the total profit of aggregator for different tax rebate values for food donation (blue line). It shows that the total profit increases with the increase in the value of the percentage of tax incentives received by the retailer, which is paid to the aggregator. Furthermore, the figure shows that the aggregator's profit increases if the tax incentive given to the retailers increases.

CO₂ emission cost from the decomposition of wasted foods along with the emission during transport is presented in Table 2 for different scenarios. The aggregator profit is maximum if 10 trucks, 25 trucks, and 4 trucks of type V_1 , V_2 , and V_3 respectively are hired. Also, we analyze that if the aggregator wants to hire only one type of truck i.e., only V_1 type of truck, only V_2 type of truck, and only V_3 type of truck then he must hire 29 trucks, 27 trucks, and 31 trucks, respectively. Similarly, our experiment entails that if aggregator can hire only two types of trucks i.e., only V_1 & V_2 type of trucks, only V_2 & V_3 type of trucks, and only V_1 & V_3 type of trucks then to maximize profit he must hire 10 of type V_1 & 27 of type V_2 , 21 of type V_2 & 7 of type V_3 , and 10 of type V_1 & 28 of type V_3 trucks respectively.

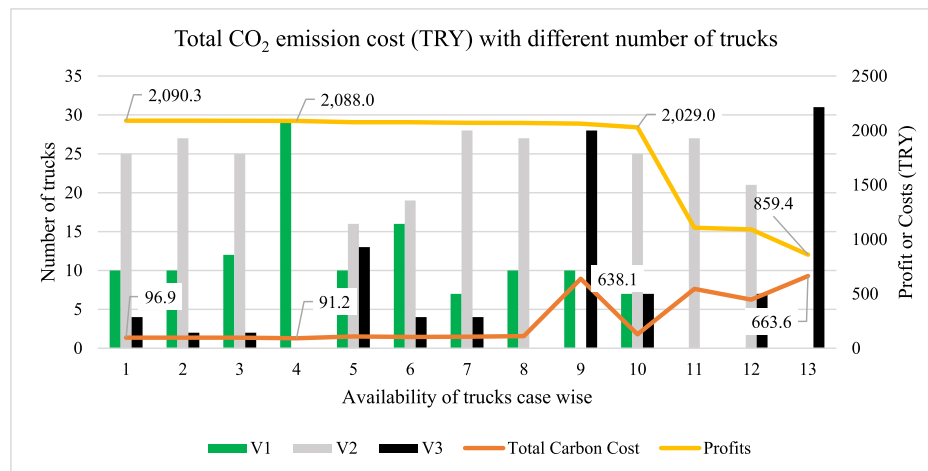
We have analyzed the environmental impact of the cold supply chain in terms of CO₂ emission cost. In Fig. 5, we have presented the total profit and CO₂ emission cost for different numbers of trucks. It can be observed that if all the trucks used are of type V_3 , the CO₂ emission cost is maximum. Since type V_3 are the larger non-refrigerated trucks, it emits more CO₂ per kilometer. On the other hand, if all the trucks used are of type V_1 , the CO₂ emission cost is minimum because type V_1 are the smaller refrigerated trucks. Also, as shown in case 4 (Fig. 5), when only V_1 type trucks are used, HFC emissions reach the highest value i.e., 1.4 TRY (also provided in Table 2). But the CO₂ emission costs for the same case are almost similar to the optimal scenario as in case 1 (Fig. 5). Given that HFCs are much stronger than other greenhouse gases, the aggregator must avoid using a fleet of only refrigerated vehicles.

Next, we present two propositions with a corollary to generate further insights for the aggregator.

Proposition 1. The quantity of product p donated by retailer r that will

Table 2Total profit, CO₂ emission cost, and HFC cost for different numbers of trucks.

CO ₂ emission Cost (TRY)			HFC Cost (TRY)	Number of trucks			Profit (TRY)
Decomposition	Transportation	Total		V ₁	V ₂	V ₃	
57.1	39.8	96.9	0.9	10.0	25.0	4.0	2090.3
65.6	37.6	103.2	1.0	16.0	19.0	4.0	2075.7
65.6	39.8	105.4	0.9	7.0	28.0	4.0	2070.6
57.1	40.0	97.1	0.9	10.0	27.0	2.0	2090.0
56.9	50.9	107.7	0.9	10.0	16.0	13.0	2075.9
86.6	40.7	127.3	0.9	7.0	25.0	7.0	2029.0
57.1	40.5	97.6	0.9	12.0	25.0	2.0	2089.3
60.0	31.2	91.2	1.4	29.0	0.0	0.0	2088.0
517.3	27.7	545.0	0.0	0.0	27.0	0.0	1107.2
628.9	34.7	663.6	0.0	0.0	0.0	31.0	859.4
406.3	40.0	446.3	0.0	0.0	21.0	7.0	1091.6
50.5	61.3	111.8	0.9	10.0	27.0	0.0	2069.1
51.6	586.5	638.1	0.9	10.0	0.0	28.0	2063.3

**Fig. 5.** Total profit and CO₂ emission cost (TRY) for different numbers of trucks.

remain consumable if sent to food bank *b* on vehicle *v* can be calculated using

$q_{rbpv} = (S_{pv})^{\frac{dist_{rb}}{speed_{rbv}}}$, where S_{pv} represents the percentage of product *p* that survives after traveling on vehicle *v* for a unit time period.

Proof: Let us assume the retailer donates 10 kg apple. Out of these, 9.5 kg will remain consumable if carried by a non-refrigerated vehicle *v* for 1 h. Alternatively, 5% of the product deteriorates in one hour when sent by vehicle *v* that is not refrigerated. The question is how much of 9.5 kg will be left if the product is transported on the same vehicle for another 1 h. The answer is 95% of 9.5 kg. It indicates the nature of the deterioration that we observe in real life and can be modeled using power functions of the form $f(x) = a \cdot x^b$ where $a, b > 0$. $\frac{dist_{rb}}{speed_{rbv}}$ = time taken by vehicle *v* to travel from retailer *r* to food bank *b*. Given $S_{pv} < 1$, for $\frac{dist_{rb}}{speed_{rbv}} > 1$, we can verify that $q_{rbpv} < S_{pv}$; when $\frac{dist_{rb}}{speed_{rbv}} < 1$, we can ascertain that $q_{rbpv} > S_{pv}$. Similarly, when time taken by the vehicle is assumed to be zero, the q_{rbpv} will simply be one,

indicating no deterioration at all. It means that when distance increases, time taken by the vehicle to travel from source to destination increases. When speed increases, the time taken by the vehicle to travel from source to destination decreases. More the time period for which a food product remains in transit, the greater the overall deterioration will be, and vice versa.

Hence, we can say that $q_{rbpv} = (S_{pv})^{\frac{dist_{rb}}{speed_{rbv}}}$, adequately represents the quantity that will survive from retailer *r* to food bank *b* on vehicle *v*.

Proposition 2. As distance or traffic increases, the aggregator requires more refrigerated vehicles.

Proof: Percentage quantity of product *p* that will remain consumable upon reaching food bank *b* from retailer *r* is given by $q_{rbpv} = (S_{pv})^{\frac{dist_{rb}}{speed_{rbv}}}$, where S_{pv} represents the percentage of product *p* that would survive after an hour in vehicle *v*. The difference in quantity that will survive after traveling the distance from retailer *r* to food bank *b* at a certain fixed speed in two different

Table 3

Optimal number of vehicles to be hired for various percentage of increase in distance.

Distance	Number of trucks			Profit (TRY)	Disposal cost (TRY)	CO ₂ emission cost (TRY)		
	V ₁	V ₂	V ₃			Decomposition	Transportation	Total
100%	10	25	4	2090.3	44.8	57.1	39.8	96.9
125%	10	26	6	1807.9	133.1	169.3	64.4	233.8
150%	13	26	10	1766.5	149.9	190.7	61.1	251.8
175%	7	25	7	1752.5	149.7	190.5	69.8	260.3
200%	11	20	1	1732.4	150.9	192.1	80.3	272.35
225%	12	15	0	1614.6	189.1	240.6	84.5	325.1
250%	16	16	1	1574.1	198.3	252.4	94.9	347.2

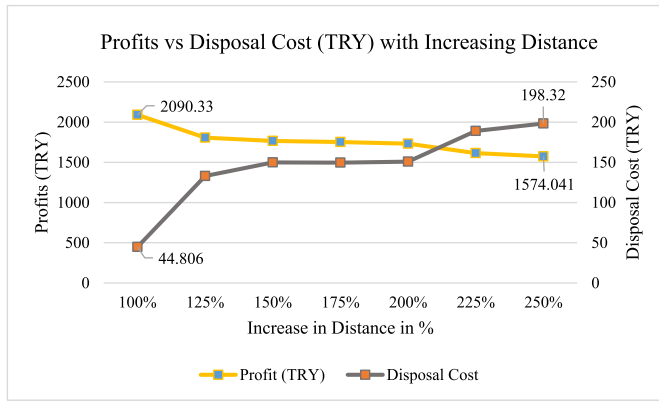


Fig. 6. Total profit and disposal cost for increasing distance in percentage.

types of vehicle would be $(S_{p1})^{\frac{dist_{rh}}{speed_{rb1}}} - (S_{p2})^{\frac{dist_{rh}}{speed_{rb2}}}$. For small difference in S_{p1} and S_{p2} , the quantity that will survive gets magnified over a larger distance when speed of both the vehicles are considered the same (since if $S_{p1} > S_{p2}$ then $(S_{p1})^{\frac{dist_{rh}}{speed_{rb1}}} >> (S_{p2})^{\frac{dist_{rh}}{speed_{rb2}}}$ for large distances). In other words, for larger distances, a small change in survival rate will lead to a huge difference in profit. Similarly, due to traffic congestion in urban areas, the vehicle will not move fast and similar results will follow. Therefore, for larger distance or urban areas it is better to use refrigerated vehicles. Our numerical analysis as presented in the results and discussion section and in Table 3 shows similar results when distance is increased and therefore validates the model.

Corollary 1. If the aggregator is not able to hire refrigerated vehicles, we must prefer satisfying demand at local food banks.

Proposition 2 infers that when the distance between source and destination increases, it is profitable to hire refrigerated vehicles. Without loss of generality, we can also infer that when distance is not large, aggregators can rely on non-refrigerated vehicles. Since the hiring of refrigerated vehicles is subject to its availability, it can be concluded that when an aggregator is not able to hire refrigerated vehicles, it must focus on routing donated food products to nearby food banks.

It is observed that, as the distance between the source and destination increases, the quantity being disposed of by the aggregator or the quantity spoiled during transport increases. Therefore, the disposal cost increases (Fig. 6). Also, we see that profit decreases as distance increases. Although there is a sharp increase in disposal costs, it does not increase significantly after 150% of the distance. For larger distance, more refrigerated vehicles are used by the aggregator (see Table 3). Moreover, for larger distances, disposal cost becomes less sensitive to distance because in such cases most of the vehicles hired are refrigerated. As obvious, the CO_2 emission costs increase as the distance increases.

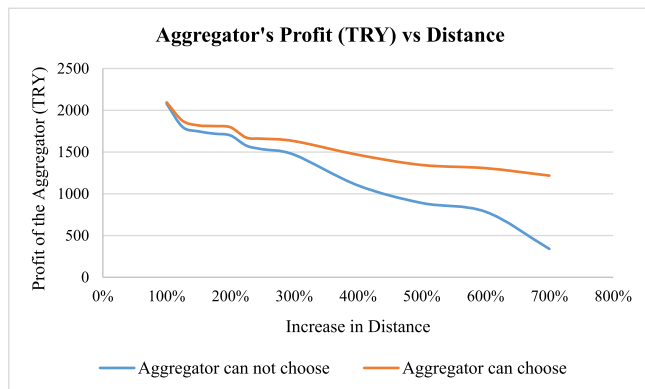


Fig. 7. The change in profit comparing the two strategies adopted by the aggregator.

When distance increases, more refrigerated vehicles are hired as shown in Table 3. This finding also validates Proposition 2.

We further analyze the results considering two different strategies which the aggregator can follow while accepting products from the retailers.

Strategy 1: When aggregator accepts the entire quantity that retailers donate:

In this case, the aggregator has to dispose of the items if it does not survive during the time it gets transported. This strategy ensures that screening is not required at the retailer's store. However, if the products are not screened, it leads to excessive deterioration on the way and the aggregator has to incur additional cost to dispose of the non-consumable items.

Strategy 2: When aggregator is allowed to reject donated items:

In this case, the aggregator screens the product before transporting it to any of the food banks. This ensures that the aggregator does not have to carry the burden of products that would not survive the journey from retailer to the food bank. In this case, Q_{rp} in equations (1) and (2) will be replaced by $\sum_{b \in B} \sum_{t \in T} y_{rbtpv}$. Fig. 7 portrays how the profit of the aggregator

varies as the distance increases for both the strategies. It can be seen that the profit decreases rapidly when the aggregator chooses strategy 1 over 2. It means that if the distance between the retailer and food bank is high, the aggregator must make sure that it accepts only better quality products from the retailer, or else the cost of disposing of the non-consumable products will surpass the benefit from the operation. Thus, the aggregator needs to make an effort for screening the products of acceptable quality for transporting the food to distant food banks.

Moreover, using strategy 2, the aggregator can determine how much of certain donated products to accept from a given retailer at a given point in time considering the availability of certain types of vehicles. Now assuming the aggregator is free to decide whether to accept or reject the products donated by the retailer, we analyzed how the quantity of product transported varied for different values of tax incentives. Our results suggest that at low values of tax-incentive, the aggregator avoids accepting highly perishable products like milk, tomato, banana and beans (see Fig. 8). However, there is no significant effect of changing values of tax-incentive on less perishable products like potato, pumpkin, onion, carrot etc. Our analysis indicates that the government may consider product-specific tax incentives to encourage and improve food delivery operations to food banks.

6. Conclusion

This study formulates a strategic mathematical decision model that combines the decision regarding the pickup of near expiry food from the

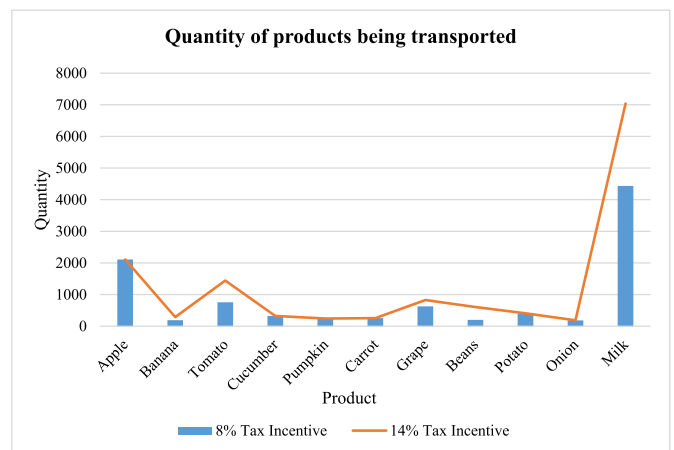


Fig. 8. The change in quantity of product being transported for various values of tax-incentives

retailers and the delivery of the food eligible to be consumed to the food bank warehouses. It designs the retailer-foodbank supply chain network by allocating the donated food from retailers to food banks with environmental considerations where the aggregator acts as an intermediate agent. The model considers different cost components such as pickup and delivery cost of food, penalty costs for violating time window both for retailers and food banks, transportation costs, waste disposal costs, and CO₂-equivalent costs during transportation and waste disposal. It accounts for realistic considerations such as time window restriction at the retailers and food banks, and quality degradation of the food being delivered. The proposed model is tested using real data from a food aggregator in Turkey. The results show how the number of hired vehicles affects the aggregator's profit, carbon costs and HFCs emitted. Furthermore, the effect of various model parameters on the total profit and CO₂/HFCs emissions along with impact of distances on types of vehicles hired is also analyzed. The impact of two strategies by the aggregator i.e., accepting and not accepting all products from the retailer on the aggregator's profit, is also analyzed.

Future research opportunities include considering the case where aggregators will use their own vehicles to transport food and they will hire the vehicles only when their own vehicles are unavailable for pickup. As a future research, uncertainty about the volume of donated food can be incorporated in the model making it stochastic in nature that can be validated using discrete event simulation. Furthermore, we can use the Life Cycle Assessment (LCA) as a tool for analyzing impact of food wastage and transportation of donated food in the retailer-food bank supply chain. LCA is an effective method to provide a thorough analysis of the overall environmental impact of the proposed solution. In this study, the hired trucks are operated at a single temperature. Considering vehicles with multiple-temperature zones for transporting food with different temperature requirements can be another possible extension of this research. In the current problem, the percentage of the tax incentive shared by the retailer with the aggregator has been considered as a parameter. If the above percentage is considered as a variable, the problem can also be modeled as a game where the retailer and the aggregator can try to determine the equilibrium level of shared tax incentives, which will maximize profits for both. From a policy perspective, the government can also try to find out the optimum level of tax incentive to provide to the retailers.

The proposed model and the results will also encourage entrepreneurs to act as aggregators and earn profit while addressing the critical problems of wastage of food and food security. The paper also has policy implications as it can inform the governments of different countries who face the dual problem of needy people not having food and food wastage in retail at the same time to incentivize retailers to share the food with food banks instead of disposing them of.

CRedit authorship contribution statement

Jasashwi Mandal: Methodology, Writing – original draft, Writing – review & editing. **Rony Mitra:** Software, Validation. **Vishal Kumar Gupta:** Formal analysis, Investigation, Visualization. **Nachiappan Subramanian:** Conceptualization, Supervision. **Yaşanur Kayikci:** Conceptualization, Data curation. **Manoj Kumar Tiwari:** Resources, Supervision, Funding acquisition.

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.

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