

Article

Vehicles Allocation for Fruit Distribution Considering CO₂ Emissions and Decisions on Subcontracting

Rafael Tordecilla-Madera ¹, Andrés Polo ^{1,*}  and Adrián Cañón ² 

¹ Program of Industrial Engineering, Fundación Universitaria Agraria de Colombia, Calle 170#54A-10, Bogotá 111166, Colombia; tordecilla.rafael@uniagraria.edu.co

² Faculty of Administration, Finance and Economic Sciences, Universidad EAN, Calle 79#11-45, Bogotá 110221, Colombia; hacanon@universidadean.edu.co

* Correspondence: polo.andres@uniagraria.edu.co

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Abstract: An important problem in rural-area supply chains is how to transport the harvested fruit to urban areas. Low- and medium-capacity vehicles are used in Colombia to carry out this activity. Operating them comes with an inherent cost and generates carbon emissions. Normally, minimizing operating costs and minimizing carbon emissions are conflicting objectives to allocate such vehicles efficiently in any of the supply chain echelons. We designed a multi-objective mixed-integer programming model to address this problem and solved it via the ϵ -constraint method. It includes decisions mainly about quantities of fruit to transport and store, types of vehicles to allocate according to their capacities, CO₂ emission levels of these vehicles, and subcontracting on the collection process. The main results show two schedules for allocating the vehicles, showing minimum and maximum CO₂ emissions. Minimum CO₂ emissions scheme require subcontracting and the maximum CO₂ scheme does not. Then, a Pareto frontier shows that CO₂ emissions level are inversely proportional to total management cost for different scenarios in which fruit supply was modified.

Keywords: CO₂ emissions; fruits supply chain; ϵ -constraint method; perishable food transportation

1. Introduction

Fresh foods such as fruits are highly perishable, which means their shelf life is limited over time. In addition, unlike other products, their quality decreases continuously during the activities of the supply chain. Therefore, the process of dealing with food supply chain networks is complicated, with respect to other types of products that flow in this type of networks [1]. These products are easily affected by environmental factors and rot in the process of circulation and flow through the supply chain [2]. Given that perishable products reduce its value over time, one of the main objectives in the distribution of these products, especially in the food supply chains, is to attend to their freshness while delivering them to the demand areas. This objective creates a direct effect on the response capacity of the network. Considering these facts, choosing an advantageous distribution network is a key factor for the logistics system administrator. Therefore, food supply chains focus on the quality of the products and the minimization of shipping times or the maximization of the quality of the products in the delivery time, especially due to the challenges associated with seasonality, supply peaks, long delivery times and perishability [3].

In addition to transport costs and response capacity in the optimization of a logistics system, the sustainable characteristics of the network must also be considered [1]. The importance of the environment is an issue that has been gaining strength for years in global production schemes. Due to the observation of the consequences of the use of non-environmentally friendly technologies, companies must go beyond social and volunteer environmental initiatives [4]. One of the biggest

challenges for sustainable business models is to achieve a scale of operations that is adequate to satisfy the quantity and depth of needs in their markets [5]. The daily growth and development of distribution companies has increased the amount of greenhouse gas (GHG) emissions, especially carbon dioxide (CO₂).

According to Cai et al. [6], there is a link between the consumption of clean energy, economic growth and CO₂ emissions. For Wang [7], it is necessary to create energies that do not emit or rarely emit greenhouse gases to favor a low carbon economy. To achieve this type of economy, the supply chain represents one of the main opportunities to improve the development of energy efficiency, even for small companies [8]. In the supply chains, some alternative fuels such as biodiesel can be implemented, thus becoming drivers of the use of sustainable energy [9]. Along these lines, impact assessments of carbon emission mitigation policies require appropriate emission models and indicators of transport logistics activity in supply chains [10]. Therefore, there is a need to integrate environmentally sound options in the consumption of clean energy in the research and practice of supply chain management [11] to finally make them green and competitive, based on the reduction of ecological impact of core activities, cost reduction, quality, performance and energy efficiency [12].

Nearly 86% of CO₂ emissions are from fossil fuels [13] and 40% of GHG emissions up to 2010 were attributed to transport. Of these, carbon emissions from road transport represented 70% [14,15]. Wang et al. [16] mentioned that supply chains are responsible for more than 20% of global GHG emissions. Therefore, the effects on the environment of vehicles distributing products must be considered to design a green supply distribution network. This can benefit the company, since it has been proved that companies that implement strategies to improve the environment can increase their product sales and market share [17].

Compared to a traditional supply chain, a chain designed to have lower carbon emissions faces additional challenges in its development. Examples of these problems can be high investment in reducing emissions when changing technologies or coordinating deliveries to maximize the supply chain's profits, especially if they are perishable products. The implementation of sustainability practices has spread, and studies have analyzed their impact on performance, that is, efficiency, flexibility and responsiveness [18,19]. According to Bourlakis et al. [20], these practices are aimed at protecting the environment to respond to external pressures, which is why these chains need to be managed efficiently and ecologically to improve environmental and social aspects [21].

In the light of the United Nations Framework Convention on Climate Change, Colombia has voluntarily committed to reducing GHG emissions by 20% by 2030. Hence, the country is positioned as an ambitious and proactive country in these issues, which constitutes an advance towards the fulfillment of the Sustainable Development Goals (SDGs) [22]. The country has estimated that land transport (light and freight vehicles) constitutes the main source of GHG emission due to the consumption of diesel and gasoline. The nationwide distribution of emissions is determined by the distribution of population and by the intensity of commercial and industrial activity. For the capital of the Republic, Bogotá, it has been estimated that the consumption of fossil fuels in transport generates 10.59 million tons of CO₂. The mobility dynamics of the country's capital means that 45% of emissions are generated by land transport, specifically by the transport of cargo and passengers in public transport. In this case, the production of CO₂, generated because of land transport in Bogotá, is a problem that affects the environment by increasing the greenhouse effect as well as affecting the cost of travel in land transport including the design of the transport network. This increase in emissions is due to the precarious transport infrastructure in remote areas branching from main roads.

The main advantage of considering the calculation of CO₂ emissions in the design of a fruit supply chain to Bogotá is the implementation of measures to reduce and compensate emissions in the design decisions on the collection routes of this product [23]. These strategies to transport perishable products generate a higher complexity for the administrator of the supply chain because these products must be transported quickly towards the wholesale markets to avoid their deterioration. That perishability condition prevents producers in rural areas to store these products for a long time [24]. To guarantee that products arrive in adequate conditions, it is necessary to identify production zones as well as

access routes to schedule times for collection, design routes for transportation, identify collection points, systematize the information to deliver products on time, compare different types of transportation [25] and determine costs associated with reducing emissions released in the transport of perishable products. This article deals with a supply chain of collection and distribution of perishable products in rural areas near the city of Bogotá. The proposed solution method seeks to establish an optimal allocation of vehicles that minimizes the total cost of transport and the CO₂ emissions generated by the supply chain. The methodological proposal has been implemented with real data from an Association of fruit producers in the department of Cundinamarca, Colombia. We addressed a tactical-operational problem and solved it through a mixed-integer programming model.

In the framework of the described context, this article seeks to make contributions aimed at improving supply chains in the environmental and performance aspects for perishable products. The main intended contributions are listed below. Firstly, we analyze a supply chain for perishable products and its reduction of carbon emissions. This paper addresses the theoretical and applied study of the impacts generated by the reduction of carbon emissions in tactical-operational decisions. We accomplish this by studying five scenarios, which include different types of vehicles as well as different forms of transport service acquisition (personal vs. subcontracted vehicles). Different ways of acquiring the service are included in the modeling because it is a practice currently carried out by different fruit producing associations in the study area. Secondly, we analyze whether the supply chain considered in this article achieves lower costs and lower CO₂ emissions for different variations of fruit supply considering a tactical problem of operations that generates a weekly plan of allocation of vehicles.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the methodology used to solve the problem and the formulation of the mathematical model that represents it. Section 4 uses an applied example of a real case of fruit distribution to illustrate the theoretical results. Section 5 analyzes the results, regarding to impacts of variations in fruit supply under normal conditions and related to CO₂ emissions in distribution route planning. The conclusions are presented in the final section.

2. Literature Review

The research literature related to the work presented in this article has two aspects: studies of CO₂ reduction in the distribution of perishable products in Colombia and supply chain models with restrictions on the reduction of carbon emissions on a general level.

2.1. CO₂ Reduction in Supply Chains

The relationships among energy consumption, CO₂ emissions and macroeconomic variables, in particular the correlations among energy consumption, CO₂ emissions and GDP growth, have attracted many researchers [26]. To investigate the link between clean energy consumption, economic growth and CO₂ emissions, Cai et al. [6] used an ARDL Bootstrap bound test in G7 countries. Their results show that, to achieve a low carbon economy, it is necessary to invest in the consumption of renewable energy. Helgesen et al. [27] linked a bottom-up energy system model (TIMES) and a top-down computable general equilibrium model (REMES) and indicated a reduction of CO₂ emissions from transport in Norway in 2030 to 50% compared to the CO₂ emissions produced in 1990. Dente and Tavasszy [10] suggested the use of the ton-kilometer indicator to measure logistics activity and emissions. In general, the ton-kilometer indicator is used to measure logistics activity, and emissions are calculated as a linear function of this indicator.

Supply chain management of perishable products is different from the supply chain management for articles that have a relatively longer shelf-life [28].

As perishable food supply chains become more complex, incidents of contamination increase [29]. Some of these incidents are related to non-optimized management during supply chain processes [30]. At present, mathematical modeling proposes to optimize certain processes for these supply chains

and reduce the decay of perishable products, but mainly deal with local production, inventory, distribution and retailing of these products [31]. Supply chains for perishable products such as fruits are often more complex and more difficult to administer since food products have a short shelf-life [32]. Unfortunately, the chains of perishable products consume a lot of energy [33] to prevent these products from decaying, and increase the emission rates, especially CO₂ [29].

One of the strategies used to reduce the emission rates is that used by Yang et al. [34], who stated that it is more effective to establish larger carbon quotas penalizing those companies that pollute the most. The problem is that a large investment has to be made to improve those polluting technologies. Another alternative to reduce emissions is the joint consideration of delays in payments for those polluting companies [35]. These authors showed that the optimization of the production rate, the duration of the delay in payments or the size of the batch provides the optimal solution for carbon emissions and the cost of a supply chain system. Bouchery et al. [36] compared management costs and carbon emissions resulting from a non-coordinated two-echelon serial economic order quantity model to that of the centralized solution; their results show that coordination allows to reduce both costs and emissions in a supply chain.

2.2. CO₂ Reduction in the Distribution of Perishable Products in Colombia

Small farmers who supply food to the city of Bogotá face different challenges that endanger their means of subsistence and, by extension, the food security of the capital of Colombia [37]. There are climatic, social, economic and environmental aspects, among others threatening the wellbeing of producers and population in general. The environmental aspects are currently in the initial stage of study. While many different strategies are needed at the national and local levels to address the increase in GHG emissions, solutions at the local level can play an important role in mitigating environmental quality problems in low- and middle-income countries such as Colombia [38]. Fruit transport operations in rural areas of Colombia are generally characterized by the absence of technology to improve the conditions in which they move, reducing the competitiveness of the country's agricultural sector [5,39].

According to Reina and Adarme [40], in Colombia, there are few studies in the field of distribution logistics of perishable products, and there are no investigations related to the initial phases of the distribution process or the reduction of CO₂ emissions. The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety [41] established that the total number of motor transport vehicles in Colombia is composed of about 250,000 cars of different capacities and ages. From that fleet, about a third is over 30 years old and generates the largest proportion of CO₂ emissions and air pollution. It is estimated that this type of vehicles is used by small transporters in rural areas to take their products to large cities for sale.

In relation to studies about GHG emissions, Cuellar et al. [42] compared different sources of CO₂ in the means of transport in Bogotá. His main result showed that public transport is not the main source of emissions. Consequently, he recommended undertaking studies on other sources of pollution such as cargo trucks. Regarding the territorial analysis of the emissions, the results of Rios [43] revealed that the most polluting places in the city of Medellín have the lowest population densities and the lowest variety of land uses. Thus, CO₂ emissions seem to be emitted by old vehicles. Román et al. [44] determined the drivers of change in CO₂ emissions between 1990 and 2012 in Colombia. This study analyzed the measures implemented by the Colombian authorities to mitigate polluting emissions, including the substitution of fossil fuels. The results allowed for the conclusion that efficiency and energy-saving policies are effective and should focus on three sectors: industrial, transport and residential.

For the transport sector, Valenzuela et al. [45] developed a model to estimate the GHG emissions generated by that sector in 2010. In this model, national emissions were projected for the 2010–2040 period, using Kaya factors. With these factors, various options were evaluated to mitigate emissions through a cost-effectiveness analysis. The results show that the country must enter a stage of

increase in gasoline fuel savings to contribute to a reduction in CO₂ generation [46], indicated from their analysis of information that the Clean Development Mechanism projects implemented in Colombia since 2000 showed a reduction of 0.78%. This result is relatively low compared to countries such as China and India. Cardenas et al. [47] analyzed the effect of tax on carbon emissions and indicated that it has not reduced the use of fossil fuels in the country. However, simulations on this type of initiative indicate that evidently the cargo transport sector in Colombia will reduce the intensity of carbon emissions as a result of the adoption of technological strategies such as replacement of engines. There can also be a significant reduction through reduced use of means of transport, clearly with an improvement in the dimension of integrated spatial development (PTCI_Space) based mainly on its connectivity through a wide network of roads and transport systems [48].

To date, no studies have analyzed the relationship between the transportation of perishable products from rural areas near the city of Bogotá and the GHG emissions released by the vehicles that carry out these operations. According to Valenzuela et al. [45], efforts should be made for perishable products to travel shorter distances and to help reduce carbon emissions, which are the main driver of climate change.

2.3. Distribution Models of Perishable Products with Carbon Emission Reduction Constrains

Although harder emission controls on vehicles have reduced harmful gas emissions, attention has shifted towards the growth of CO₂ emissions from the cargo transport sector [8,49]. In recent years, the development and application of operations research models in supply chains of perishable products have attracted many researchers in different countries [1]. For example, Soysal et al. [50] performed an analysis of a fresh tomato supply chain including distribution costs dependent on truck load for a comprehensive assessment of CO₂ emissions and fuel consumption. Volpe et al. [51] calculated CO₂ emissions for all stages of the production chain from nut-based products to the final point of sale; Yang et al. [52] analyzed the decay process of perishable foods and determined the optimal temperature of the chain of cold with minimal emissions; and Gallo et al. [53] conducted a study, using mixed integer linear programming, for the design of sustainable supply chains for the distribution of fresh apples and ice cream. The number of researchers that link product perishability and transport emissions has risen [54]. Validi et al. [55] proposed a bi-objective model for the distribution of milk in Ireland. Their model minimizes the total cost and CO₂ emissions in distribution channels. The presented sustainable distribution process allows to the supply chain decision maker to reduce the total carbon emission of the transport involved in the entire distribution process, while optimizing the total costs. Bortolini et al. [56] studied a distribution network of products grown in Italy and distributed in several European markets. Their study considered three objectives: total operating costs, total CO₂ emissions and delivery time of the products. Their results showed that the multi-objective perspective is of great help since it allows to reduce CO₂ emissions with a limited cost increase and an admissible delivery time. The carbon reduction is equal to 9.6% and the increase of the operating cost is of 2.7% compared to the traditional distribution network configuration. Soysal et al. [57] analyzed the benefits of horizontal collaboration related to product perishability, CO₂ emissions from transport operations and logistics costs in the Inventory Routing Problem (IRP) with multiple suppliers and customers. Through the development of a decision support model, their results indicated that the horizontal collaboration among suppliers allows reducing the aggregate total cost by 17% and the aggregate total CO₂ emissions by 29% in the case studied.

3. Methodology

The problem addressed in this article deals with the allocation of vehicles for the collection, transport and distribution of fruit from producers to sale points, passing through several intermediate points that are necessary for collection and better distribution. In particular, it is considered that there are two types of collection points, that is, the producers are divided into two groups. Some located on routes (a route is a group of producers with low fruit production) whose initial collection is done in a

first location and from there they are transported to a storage center of greater capacity. The producers of the other group directly transport the harvested fruit to these collection centers, which are considered individually in the model because they produce much more fruit than those located on the routes. In addition, the collection on routes and from individual producers can be subcontracted.

Then, the fruit is transported from these collection centers to customers (wholesale centers) located in a city or urban center. For this case, customers are considered to be on a pre-established route, in such a way that the vehicles distribute the fruit by visiting customers one after the other. Figure 1 shows a diagram of the supply chain considered.

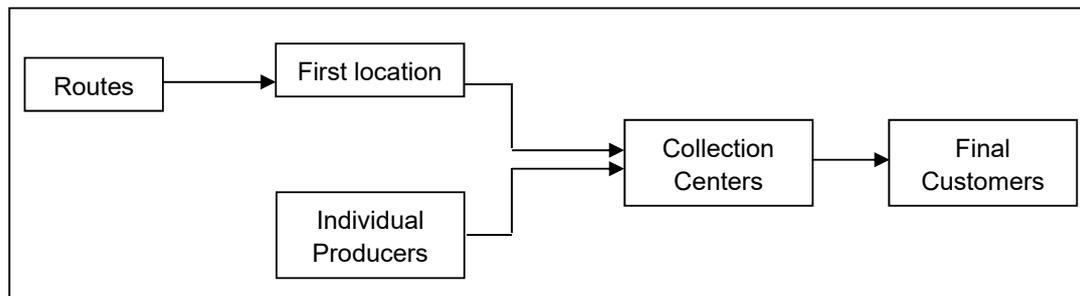


Figure 1. Configuration of the supply chain.

To solve this problem, we designed a multi-objective mixed-integer programming model, which seeks to minimize both the total cost of management and the level of CO₂ emissions of vehicles. The formulation of the problem is presented below.

3.1. Sets

- I = Set of routes to the first location
- M = Set of individual fruit producers not located on a route
- J = Set of collection centers
- K = Set of final customers
- L = Set of types of vehicles
- T = Set of days of the week

3.2. Parameters

- CK_l = Variable transport cost (\$/(kg km)) in vehicle $l \in L$
- CKm_l = Transportation fixed cost (\$/km) in vehicle $l \in L$
- CY_i = Fixed cost (\$) if the collection is subcontracted in route $i \in I$
- CYA_{mj} = Fixed cost (\$) if collection is subcontracted from the producer $m \in M$ to the collection center $j \in J$
- CP_l = Cost of toll payment (\$) on the road that vehicle $l \in L$ must pay
- CC_{kl} = Parking cost (\$) of vehicle $l \in L$ at the customer's $k \in K$ facility
- h_j = Fixed cost (\$/week) for using collection center $j \in J$
- EA_i = Supply (kg/week) from route $i \in I$
- EB_m = Supply (kg/week) from producer $m \in M$
- D_k = Demand (kg/week) from customer $k \in K$
- CAP_j = Capacity (kg/week) of collection center $j \in J$
- G_l = Capacity (kg) of vehicle $l \in L$
- DD_i = Length (km) of route $i \in I$
- DA_{mj} = Distance (km) from producer $m \in M$ to collection center $j \in J$
- DB_j = Distance (km) from the first location to collection Center 1
- DC_{jk} = Distance (km) from collection center $j \in J$ to Customer 1
- DE_{kk} = Distance (km) from Customer 1 to Customer 2

DT_l = Maximum distance (km/day) vehicle $l \in L$ can travel
 NV_l = Number of available vehicles type $l \in L$
 EM_l = Quantity of vehicle $l \in L$ emissions (kgCO₂/(kg km))
 Mm = Very large number

3.3. Variables

x_{ilt} = Quantity of fruit (kg/day) transported on route $i \in I$ to the first location in vehicle $l \in L$ on day $t \in T$
 xv_{ilt} = Number of trips to be made on route $i \in I$ to the first location in vehicle $l \in L$ on day $t \in T$
 y_{it} = Binary that indicates whether or not the collection is subcontracted in route $i \in I$ on day $t \in T$
 xs_{it} = Quantity of fruit (kg/day) whose harvest is subcontracted in route $i \in I$ on day $t \in T$
 Q_{jlt} = Amount of fruit (kg/day) transported from the first location to the collection Center 1 in vehicle $l \in L$ on day $t \in T$
 QV_{jlt} = Number of trips to be made from the first location to collection Center 1 in vehicle $l \in L$ on day $t \in T$
 TP_{mjlt} = Quantity of fruit (kg/day) transported from producer $m \in M$ to storage center $j \in J$ in vehicle $l \in L$ on day $t \in T$
 PV_{mjlt} = Number of trips to be made from producer $m \in M$ to storage center $j \in J$ in vehicle $l \in L$ on day $t \in T$
 U_{mjt} = Binary that indicates whether or not the harvest is subcontracted from producer $m \in M$ to collection center $j \in J$ on day $t \in T$
 PS_{mjt} = Amount of fruit (kg/day) whose harvest is subcontracted from producer $m \in M$ to storage center $j \in J$ on day $t \in T$
 W_{jklt} = Amount of fruit (kg/day) transported from the storage center $j \in J$ to Customer 1 in vehicle $l \in L$ on day $t \in T$
 WV_{jklt} = Number of trips to be made from collection center $j \in J$ to Client 1 in vehicle $l \in L$ on day $t \in T$
 $V_{kk'lt}$ = Quantity of fruit (kg/day) transported from Customer 1 to Customer 2 in vehicle $l \in L$ on day $t \in T$
 $VV_{kk'lt}$ = Number of trips to be made from Customer 1 to Customer 2 in vehicle $l \in L$ on day $t \in T$
 INV_{jt} = Amount of fruit (kg/day) left in collection center $j \in J$ at the end of day $t \in T$
 $INVA_j$ = Binary that indicates whether the storage center $j \in J$ is used or not
 $INVB_{jt}$ = Binary that indicates whether the storage center $j \in J$ is used or not at the end of day $t \in T$
 $DAUX_{kt}$ = Amount of fruit (kg/day) that is distributed to Customer 1 on day $t \in T$
 ZTT = Total amount of CO₂ (kg/week) expelled
 CT = Total cost of management (\$/week)

3.4. Model

By using the above notation, a multi-objective mixed-integer programming model to minimize the total cost and the total CO₂ emissions is formulated as follows:

Objective 1: Min CT

$$\begin{aligned}
 &= \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} [1.5CK_l DD_i x_{ilt} + 2CK_{m_l} DD_i xv_{ilt}] + \sum_{i \in I} \sum_{t \in T} [CY_i y_{it}] \\
 &+ \sum_{j=1} \sum_{l \in L} \sum_{t \in T} [CK_l DB_j Q_{jlt} + 2CK_{m_l} DB_j QV_{jlt}] \\
 &+ \sum_{m \in M} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} [CK_l DA_{mj} P_{mjlt} + 2CK_{m_l} DA_{mj} PV_{mjlt}] \\
 &+ \sum_{m \in M} \sum_{j \in J} \sum_{t \in T} [CYA_{mj} U_{mjt}] \\
 &+ \sum_{j \in J} \sum_{k=1} \sum_{l \in L} \sum_{t \in T} [CK_l DC_{jk} W_{jklt} + (2CK_{m_l} DC_{jk} + 2CP_l + CC_{kl}) WV_{jklt}] \\
 &+ \sum_{k=1} \sum_{k'=2} \sum_{l \in L} \sum_{t \in T} [CK_l DE_{kk'} V_{kk'lt} + (2CK_{m_l} DE_{kk'} + CC_{k'l}) VV_{kk'lt}] \\
 &+ \sum_{j \in J} [h_j INVA_j]
 \end{aligned} \tag{1}$$

Objective 2 : Min ZTT

$$= \sum_{l \in L} EM_l \left[\sum_{i \in I} \sum_{t \in T} DD_i x_{ilt} + \sum_{j=1} \sum_{t \in T} DB_j Q_{jlt} + \sum_{m \in M} \sum_{j \in J} \sum_{t \in T} DA_{mj} P_{mjlt} \right. \\ \left. + \sum_{j \in J} \sum_{k=1} \sum_{t \in T} DC_{jk} W_{jkl} + \sum_{k=1} \sum_{k'=2} \sum_{t \in T} DE_{kk'} V_{kk'lt} \right] \quad (2)$$

s.t.

$$\sum_{l \in L} \sum_{t \in T} x_{ilt} + \sum_{t \in T} xs_{it} = EA_i \quad \forall i \in I \quad (3)$$

$$\sum_{j \in J} \sum_{l \in L} \sum_{t \in T} P_{mjlt} + \sum_{j \in J} \sum_{t \in T} PS_{mjt} = EB_m \quad \forall m \in M \quad (4)$$

$$x_{ilt} \leq G_l x v_{ilt} \quad \forall i \in I, l \in L, t \in T \quad (5)$$

$$Q_{jlt} \leq G_l Q V_{jlt} \quad \forall l \in L, t \in T, j = 1 \quad (6)$$

$$P_{mjlt} \leq G_l P V_{mjlt} \quad \forall m \in M, j \in J, l \in L, t \in T \quad (7)$$

$$W_{jkl} \leq G_l W V_{jkl} \quad \forall j \in J, l \in L, t \in T, k = 1 \quad (8)$$

$$V_{kk'lt} \leq G_l V V_{kk'lt} \quad \forall l \in L, t \in T, k = 1, k' = 2 \quad (9)$$

$$xs_{it} \leq M m Y_{it} \quad \forall i \in I, t \in T \quad (10)$$

$$PS_{mjt} \leq M m U_{mjt} \quad \forall m \in M, j \in J, t \in T \quad (11)$$

$$\sum_{i \in I} \sum_{l \in L} x_{ilt} + \sum_{i \in I} xs_{it} = \sum_{j=1} \sum_{l \in L} Q_{jlt} \quad \forall t \in T \quad (12)$$

$$INV_{jt-1} + \sum_{l \in L} Q_{jlt} + \sum_{m \in M} \sum_{l \in L} P_{mjlt} + \sum_{m \in M} PS_{mjt} - \sum_{k=1} \sum_{l \in L} W_{jkl} = INV_{jt} \quad \forall t \in T, j = 1 \quad (13)$$

$$INV_{jt-1} + \sum_{m \in M} \sum_{l \in L} P_{mjlt} + \sum_{m \in M} PS_{mjt} - \sum_{k=1} \sum_{l \in L} W_{jkl} = INV_{jt} \quad \forall t \in T, j \neq 1 \quad (14)$$

$$INV_{jt} \leq CAP_j INVB_{jt} \quad \forall j \in J, t \in T \quad (15)$$

$$INVB_{jt} \leq INVA_j \quad \forall j \in J, t \in T \quad (16)$$

$$\sum_{t \in T} INVB_{jt} \leq 2 \quad \forall j \in J \quad (17)$$

$$\sum_{k=1} \sum_{l \in L} W_{jkl} \leq M m INVB_{jt} \quad \forall j \in J, t \in T \quad (18)$$

$$\sum_{j \in J} \sum_{l \in L} W_{jkl} - \sum_{k'=2} \sum_{l \in L} V_{kk'lt} = DAUX_{kt} \quad \forall t \in T, k = 1 \quad (19)$$

$$\sum_{k'=2} V V_{kk'lt} \leq M m \sum_{j \in J} W V_{jkl} \quad \forall l \in L, t \in T, k = 1 \quad (20)$$

$$\sum_{t \in T} DAUX_{kt} = D_k \quad \forall k = 1 \quad (21)$$

$$\sum_{k'=1} \sum_{l \in L} \sum_{t \in T} V_{k'klt} = D_k \quad \forall k = 2 \quad (22)$$

$$2 \left[\sum_{i \in I} DD_i x v_{ilt} + \sum_{j=1} DB_j Q V_{jlt} + \sum_{m \in M} \sum_{j \in J} DA_{mj} P V_{mjlt} + \sum_{j \in J} \sum_{k=1} DC_{jk} W V_{jkl} + \sum_{k=1} \sum_{k'=2} DE_{kk'} V V_{kk'lt} \right] \\ \leq NV_l DT_l \quad \forall l \in L, t \in T \quad (23)$$

$$\forall x_{ilt}, xs_{it}, Q_{jlt}, P_{mjlt}, PS_{mjt}, W_{jkl}, V_{kk'lt}, INV_{jt}, DAUX_{kt}, ZA_{ilt}, ZB_{jlt}, ZC_{mjlt}, ZD_{jkl}, ZE_{kk'lt} \geq 0 \quad (24)$$

$$\forall x v_{ilt}, Q V_{jlt}, P V_{mjlt}, W V_{jkl}, V V_{kk'lt} \in \mathbb{Z}^+ \quad (25)$$

$$\forall y_{it}, U_{mjt}, INVA_j, INVB_{jt} \in \{0, 1\} \quad (26)$$

In this model, Equation (1) indicates the total cost of the management to be minimized, which includes transport costs among all links in the chain, costs of subcontracting the collection, costs for road tolls and parking at customers' facilities, and costs for collection center use. Note that the fixed costs associated with those variables that represent the number of trips are multiplied by two, because, in the objective, trips are accounted for both ways. Additionally, the variable that represents the amount of fruit collected on the routes is multiplied by 1.5, as the vehicle gradually collects fruit on the route, and returns with a full load. This indicates that, on the outgoing trip, on average, it is loaded at 0.5 of x_{ilt} , while on the return trip, it is loaded at 100% of x_{ilt} . Based on the methodology for calculating emissions by Li [58], Equation (2) minimizes the total amount of CO₂ emitted in a given week. Constraints (3) and (4) ensure that all fruit is collected, either on a route or from the individual producers, and by personal or subcontracted vehicles. Constraints (5)–(9) ensure that the amount of fruit transported does not exceed the capacity of the vehicles. Constraints (10) and (11) ensure that subcontracted transport collects fruit only if the decision is made to subcontract. Constraints (12)–(14) ensure that there is a balance in the flow of product in the first location and in the collection centers, respectively. Constraint (15) guarantees that the storage capacity of each storage center is not exceeded on any given day.

Constraint (16) ensures that a collection center is used on a given day only if it is to be used in the week to be planned. Constraint (17) indicates that it is not possible to store the fruit for more than two days, given its perishability. Constraint (18) ensures that a collection center allows product flow only if it is to be used. Constraint (19) ensures that every day there is a balance in the flow of product that passes through Customer 1. Constraint (20) ensures that each day, each type of vehicle transports fruit from Customer 1 to Customer 2 only in the case that it has been used to transport fruit from collection centers to Customer 1, in accordance with the pre-established route. Constraints (21) and (22) ensure that all fruit is delivered to customers. This is possible because all produced fruits are sold. Constraint (23) ensures that on any given day the different types of vehicles cannot exceed the maximum total distance traveled round trip. This is necessary because obviously is not possible to travel an unlimited distance in one day. Constraints (24)–(26) indicate the variables that are positive, integer and binary, respectively.

3.5. Solution Approach

The multi-objective model was solved via the ε -constraint method [54]. This method consists of optimizing a single objective, while the others are formulated as constraints. For the particular case of the present study, the minimization of Objective 1 was maintained, while Objective 2 was reformulated through Equations (27)–(29), for which the additional parameter ε = maximum permitted quantity of emissions (kg CO₂/week) and additional variable ZT_l = total quantity of CO₂ (kg/week) emitted by vehicle type l ($ZT_l \geq 0$) were previously defined.

$$ZT_l = EM_l \left[\sum_{i \in I} \sum_{t \in T} DD_i x_{ilt} + \sum_{j=1} \sum_{t \in T} DB_j Q_{jlt} + \sum_{m \in M} \sum_{j \in J} \sum_{t \in T} DA_{mj} P_{mjlt} + \sum_{j \in J} \sum_{k=1} \sum_{t \in T} DC_{jk} W_{jklt} + \sum_{k=1} \sum_{k'=2} \sum_{t \in T} DE_{kk'} V_{kk'lt} \right] \quad (27)$$

$\forall l \in L$

$$ZTT = \sum_{l \in L} ZT_l \quad (28)$$

$$ZTT \leq \varepsilon \quad (29)$$

Equation (27) calculates the quantity of CO₂ emissions emitted by each type of vehicle. Equation (28) calculates the quantity of emissions added for the type of vehicle. These two equations may be understood as intermediate steps. They are not necessary for the correct functioning of the ε -constraint method, but are important for identification of the quantity of CO₂ emitted by each vehicle,

and later analysis of the form in which the scheduling of each of these affects emissions. Constraint (29) limits emission levels.

The methodology used to restrict emissions made use of the parameters shown below: $emmax$: maximum CO₂ emissions value. This corresponds to the value of the emissions when they are unrestricted, or when the model is run without Equations (27) and (28), and Constraint (29). $emmin$ is the minimum CO₂ emissions value. This value is found by trial and error, reducing the value of ε as much as possible in Constraint (29), until the model becomes unfeasible. δ : integer parameter which varies within 1–10 to controllably limit emissions between $emmin$ and $emmax$. In general, this parameter does not have to oscillate within 0–10, but the greater the number of values considered, the greater the number of test runs to be performed. The relationship between these parameters is as shown in Equation (30).

$$\varepsilon = emmin + \frac{\delta * (emmax - emmin)}{10} \quad (30)$$

The variation of parameter δ within 0–10 in Equation (30) results in 11 values for ε , which were tested in each one of the five supply scenarios, for a total of 55 model test runs. Following said test runs, the relationship between both model objectives were established through the construction of a Pareto frontier.

4. Case Study

The case used for the test runs considers a real case from a fruit producer Association in Cundinamarca, Colombia, whose name cannot be revealed. In this case, there are four routes, eight individual producers, three collection centers, two final customers, two types of vehicles, and collection and distribution may be performed on any day from Monday to Friday. Table 1 shows the parameters associated with each type of vehicle.

Table 1. Vehicle parameters.

Parameter	Description	Vehicle Type 1	Vehicle Type 2
G_l	Load capacity (kg)	6000	1500
DT_l	Maximum distance (km/day) to be traveled	300	400
NV_l	Number of vehicles available	3	4
EM_l	Amount of emissions (gCO ₂ /(kg km))	0.40640	0.20075

This Association was established in the area with the objective of increasing bargaining power with customers, as grouping different producers with similar interests results in a large quantity of product to be negotiated. Additionally, the aggregation of this fruit reduces transport costs, which would be higher if each producer transported their goods individually, as the distances within the area are shorter than those to customers (see Table 2, in which all values are noted in km).

Initially, the model was run for five groups (scenarios) of supply values, minimizing only Objective 1. In other words, initially, CO₂ emission minimization was not considered, although it was indeed measured. As supply variations depend mainly on the time of year, and not on each producer or individual route, it is supposed that the same variations exist for all producers in the region. For this study, we consider a scenario of minimal demand, a scenario of maximum demand, and a scenario of average demand, which are based on real data provided by the producer association. Additionally, two scenarios were considered, whose supply values are located between the minimum and the average, and between the average and the maximum. Concretely, if the average supply is taken as base, the values of the supply are as shown in Table 3. On the other hand, since the product to be distributed is fruit, everything that is produced is sold to the collection centers, and, as such, the total demand will always be equal to the total supply.

Table 2. Distances (km) for different links in the chain.

Parameter	Description	Values			
DB_j	Distance from the first location to Collection Center 1	5.90			
$DE_{kk'}$	Distance from Customer 1 to Customer 2	25.00			
DD_i	Length of each route	Route 1	Route 2	Route 3	Route 4
		17.06	13.40	14.50	14.30
DA_{mj}	Distance from each producer to each collection center	J1	J2	J3	
		M1	14.10	16.80	13.10
		M2	17.60	17.50	13.30
		M3	17.60	17.90	15.60
		M4	13.70	16.40	13.30
		M5	13.20	14.90	15.40
		M6	14.10	16.40	17.30
		M7	17.30	15.70	17.20
M8	14.60	13.90	15.40		
DC_{jk}	Distance from each collection center to Client 1	95	80	110	

Table 3. Supply scenarios considered.

Scenario	Supply Considered (kg)	Total Supply (kg/Week)
1	$0.50 \times (\text{Average supply})$	23,390.50
2	$0.75 \times (\text{Average supply})$	35,085.75
3	$1.00 \times (\text{Average supply})$	46,781.00
4	$1.25 \times (\text{Average supply})$	58,476.25
5	$1.50 \times (\text{Average supply})$	70,171.50

5. Results and Analysis

The general results of the test runs are shown in Table 4. Observe that, when the supply is minimal, the minimum management cost is COP 1,155,671.15/week (COP stands for Colombian Peso, local currency), while for the scenario of maximum supply, the cost almost triples to COP 3,098,655.25/week. Similar behavior is observed for CO₂ emissions, growing from 1138.06 kg/week with the minimum supply to 3117.13 kg/week with the maximum supply. Intermediate values are observed for scenarios two, three, and four, showing a directly proportional relationship between the variables. Additionally, relationships between CO₂ emissions and total supply, and between total cost and total supply are shown. It is observed that the differences between said indicators for the various scenarios are small. As one may observe in Objective 2 (Equation (2)), the total emissions calculation not only depends on the amount of fruit transported, but also on the type of vehicle used. As is explained further on, based on the results in Table 5, the usage frequency for each type of vehicle varies in each scenario, and, from there, the slight variations in the relationship calculated in Table 4 are derived. Something similar occurs with Objective 1 (Equation (1)), in which the total cost depends on the amount transported, type of vehicle used, and number of trips made.

The concrete scheduling required to achieve these costs indicates that it is not necessary to subcontract collection for any route or producer, and as such, adequate assignment of the association's own vehicles is sufficient for collection and distribution. Said scheduling is shown in Table 5, in which R1, R2, R3, and R4 indicate whether each vehicle is assigned to collection routes, CA indicates whether transport is assigned between the first location and Collection Center 1, M1, M2, . . . , M8 indicate whether collection is assigned to individual producers, and in the row entitled "Customers", J1 and J2 indicate whether the vehicle is assigned to transport from Collection Center 1 or 2 to Customer 1. Finally, C2 indicates whether transport is assigned between Customer 1 and Customer 2. In this case, the model test runs never indicated that Collection Center 3 needed to be used, and, for this reason, it was not added to the table.

Table 4. Results of the first test runs.

Scenario	Total Supply (kg/Week)	CO ₂ Emissions (kg/Week)	Total Cost (COP/Week)	Relationship between CO ₂ Emissions and Total Supply (kgCO ₂ /kg)	Relationship between Total Cost and Total Supply (COP/kg)
1	23,390.50	1138.06	1,155,671.15	0.0487	49.41
2	35,085.75	1707.09	1,672,598.73	0.0487	47.67
3	46,781.00	2084.11	2,059,520.12	0.0446	44.02
4	58,476.25	2614.23	2,575,001.67	0.0447	44.04
5	70,171.50	3117.13	3,098,655.25	0.0444	44.16

Table 5. Daily assignment of each vehicle for each link in the chain.

Scenario	Vehicle	Link in the Chain	Day				
			Monday	Tuesday	Wednesday	Thursday	Friday
1	1	Routes J1 J2			M1, M2, M3, M6, M7		R2, R4, CA M4, M5, M8
		Customers			J1, C2		J1, C2
2	2	Routes J1 J2					R1, R3
		Customers					
2	1	Routes J1 J2				R2, CA M1, M2, M4, M6, M7, M8	R4, CA M3, M5
		Customers				J1	J1, C2
3	2	Routes J1 J2				R1	R3
		Customers					
3	1	Routes J1 J2			R1, R2, R3, R4, CA		
		Customers	M2, M5, M8 J2, C2	M1, M3, M4, M6, M7 J2	J1, C2		
4	1	Routes J1 J2			R1, R2, R3, R4, CA M1		
		Customers			J1, C2	M2, M3, M4, M6, M7 J2, C2	M1, M5, M8 J2, C2
5	2	Routes J1 J2			R4		
		Customers				M7	
5	1	Routes J1 J2		R1, R2, R3, R4, CA	R4, CA		
		Customers		J1, C2	J1, C2	M1, M3, M4, M6, M8 J2, C2	M2, M5, M7 J2
5	2	Routes J1 J2		M5	M4		
		Customers				M3, M6, M7 C2	

The minimal use given to Vehicle 2 in all supply scenarios is notable, with the exception of Scenario 5, in which its use increases not only for collection from certain individual producers, but also for distribution to customers. Thus, in Scenarios 1 and 2, Vehicle 2 is used for collection on Routes 1 and 3; in Scenario 3; it is never used, in Scenario 4, it collects on Route 4 and from Individual Producer 7; and, in Scenario 5, collects from Individual 3–7, and distributes to Customer 2. For all other scenarios and links in the chain, Vehicle 1 is used. The more intensive use of Vehicle 1 is made evident by the results shown in Table 6. There, one may observe the percentage of fruit transported by each vehicle in each link of the chain, for each scenario. The greater use given to Vehicle 2 is for fruit collection on the routes in Scenarios 1 and 2, collecting 27.8% of the fruit. Beyond this, said vehicle is used very little, if at all. It is not used in any scenario in the links which join First location and Collection centers, or those which join Collection centers and Customer 1.

Table 6. Quantity of fruit (%) transported by every type of vehicle.

Scenario	Vehicle	Routes	First	Individual	Collection	Customer
			Location–Collection Centers	Producers–Collection Centers	Centers–Customer 1	1–Customer 2
1	1	72.2	100.0	100.0	100.0	100.0
	2	27.8	0.0	0.0	0.0	0.0
2	1	72.2	100.0	100.0	100.0	100.0
	2	27.8	0.0	0.0	0.0	0.0
3	1	100.0	100.0	100.0	100.0	100.0
	2	0.0	0.0	0.0	0.0	0.0
4	1	96.1	100.0	99.6	100.0	100.0
	2	3.9	0.0	0.4	0.0	0.0
5	1	100.0	100.0	93.5	100.0	97.7
	2	0.0	0.0	6.5	0.0	2.3

These results indicate that the minimum costs attained making intensive use of 6000 kg vehicles, which is achieved by assigning them to collection and distribution on several days of the week. Thus, for Scenarios 1 and 2, two days of work would be sufficient; for Scenarios 3 and 4, three days of work; and for Scenario 5, four days of work, from Tuesday to Friday. The use of collection centers for fruit storage from one day to the next facilitates this work. Table 7 shows the quantities to be stored (kg) each day in each scenario, in each collection center. Observe that, in Scenario 1, storage from one day to the next is not necessary (although Collection Center 1 is used to collect and distribute, as shown in Table 5), Collection Center 1 is used for storage in Scenarios 2 and 5, and Collection Center 2 is used in Scenarios 3–5.

Table 7. Quantities (kg/day) of fruit inventory to be stored.

Scenario	Collection Center	Day				
		Monday	Tuesday	Wednesday	Thursday	Friday
1	J1					
	J2					
2	J1				5243.25	
	J2					
3	J1					
	J2	850.00				
4	J1					
	J2				3081.25	
5	J1		5917.50			
	J2				12,339.00	

CO₂ Emission Results

Table 8 shows emissions by type of vehicle, in the case of both maximum and minimum emissions. Additionally, the costs for the case of minimum emissions are shown. It is evident that, to reduce emissions, more intensive use of vehicles with lesser capacities (1500 kg), or even non-use of Vehicle 1 is required in Scenarios 1–4. The more intensive use of Vehicle 2 implies that the total costs increase to more than double the costs shown in Table 4 for each scenario. Likewise, CO₂ emissions can be reduced, at best, to between 39% and 51% of the maximum level, depending on the scenario. The greatest reduction is achieved for minimum supply Scenarios 1 and 2 while the 51% reduction applies to the scenario with highest supply.

Table 8. Maximum and minimum CO₂ emission levels.

Scenario	Total Supply (kg/Week)	emmax. (kgCO ₂ /Week)			emmin (kgCO ₂ /Week)				
		Vehicle 1	Vehicle 2	Total	Total Cost (COP/Week)	Vehicle 1	Vehicle 2	Total	Total Cost (COP/Week)
1	23,390.50	1133.05	5.00	1138.06	1,155,671.15	0.00	440.62	440.62	2,283,063.82
2	35,085.75	1699.58	7.50	1707.09	1,672,598.73	0.00	660.94	660.94	3,854,595.73
3	46,781.00	2084.11	0.00	2084.11	2,059,520.12	0.00	897.49	897.49	4,933,184.33
4	58,476.25	2612.16	2.07	2614.23	2,575,001.67	0.00	1171.48	1171.48	6,153,310.18
5	70,171.50	3103.47	13.65	3117.13	3,098,655.25	386.55	1192.42	1578.97	6,774,143.94

The reduction in the kg of CO₂ emitted is not just possible because of the decrease in the use of Vehicle 1, but also because of the increase in subcontracted collection routes. Naturally, this also contributes to the increase in cost, as, when the cost was minimal, in the cases of Tables 4 and 5, collection was never subcontracted. At this point, it should be clarified that CO₂ emissions expelled from subcontracted vehicles were not considered in this model, as this is not under control of the Association, in contrast to that of their own vehicles, which are scheduled at their convenience. Said scheduling, in the case of minimal emissions, is shown in Table 9.

Table 9. Daily assignment of each vehicle in each link in the chain for minimum emissions.

Scenario	Vehicle	Link in the Chain	Day				
			Monday	Tuesday	Wednesday	Thursday	Friday
1	2	Routes Customers	CA J1		CA J1, J2, C2	J2, C2	
	Subcontracted	Routes J1 J2	R1, R3, R4		R2 M4, M5, M7	M1, M2, M3, M6, M8	
2	2	Routes Customers	CA J1, C2	J2	J2, C2		CA J1, C2
	Subcontracted	Routes J1 J2	R1	M2, M3, M4, M6, M8	M1, M5, M7		R2, R3, R4
3	2	Routes Customers		CA J1, C2	CA J1, C2	J2	J2
	Subcontracted	Routes J1 J2		R1, R3, R4	R2 M4, M6	M2, M5, M7, M8	M1, M3, M4
4	2	Routes Customers	J3, C2	CA J1, C2	J1, C2	J2	J2
	Subcontracted	Routes J1 J2 J3		R1, R2, R3, R4	M4, M6	M2, M3, M5, M6, M7	M8
			M1, M2				
5	1	Routes Customers		CA		J2, C2	
	2	Routes Customers	CA J1, C2	CA J1, C2	J2	J2	J3, C2
	Subcontracted	Routes J1 J2 J3	R1, R2, R3, R4	R2 M6	M2, M3, M5, M7, M8	M1, M6	M2, M4

In the case of the results in Table 9, collection and distribution occurs for three days in supply Scenario 1, for four days in Scenarios 2 and 3, and for five days in Scenarios 4 and 5. The increase in collection–distribution days, with respect to cases in which CO₂ emissions were not restricted, is due to more intensive use of a vehicle with lesser capacity (1500 kg), as it must be used more frequently

to compensate for the supply which was covered before with a 6000 kg vehicle. For all scenarios, collection routes and individual producer collection is subcontracted, and the rest of the links are covered by Vehicle 2, with the exception of transport between the first location and Collection Center 1 (J1) on Tuesday, and transport from Collection Center 2 (J2) to both customers on Thursday, which is performed with Vehicle 1 in Scenario 5.

In contrast to the case in which CO₂ emissions are not restricted, this time Collection Center 3 is used to achieve better coverage in the collection–distribution process. Its use limits only those scenarios of greatest supply (4 and 5) and it only receives fruit from two individual producers: M1 and M2 on Monday in Scenario 4, and M2 and M4 on Friday in Scenario 5. Additionally, there is more intensive use of Collection Center 2 (J2), as in Scenarios 1 and 2, Collection Center 1 (J1) is only used to receive fruit coming off of routes, while in the other scenarios, apart from fruit coming off of routes, it is used exclusively for reception of goods from individual producers M4 and M6. For this case, in Scenarios 1–4, 100% of the fruit is transported, whether with Vehicle 2 or with subcontracted vehicles, depending on the link (Table 10). In said table, the minimal use of Vehicle 1 is demonstrated, as it is only used in Scenario 5 to transport a maximum of 16.6% of the fruit in the link which goes from Collection centers to Customer 1.

Table 10. Quantity of fruit (%) transported by every type of vehicle for minimum emissions.

Scenario	Vehicle	Routes	First Location–Collection Centers	Individual Producers–Collection Centers	Collection Centers–Customer 1	Customer 1–Customer 2
1	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	100.0	0.0	100.0	100.0
	Subcontracted	100.0	-	100.0	-	-
2	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	100.0	0.0	100.0	100.0
	Subcontracted	100.0	-	100.0	-	-
3	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	100.0	0.0	100.0	100.0
	Subcontracted	100.0	-	100.0	-	-
4	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	100.0	0.0	100.0	100.0
	Subcontracted	100.0	-	100.0	-	-
5	1	0.0	3.4	0.0	16.6	2.3
	2	0.0	96.6	0.0	83.4	97.7
	Subcontracted	100.0	-	100.0	-	-

As extreme cases, the scheduling of vehicles has been shown in detail for the cases of maximum and minimum emissions. However, model test runs were performed for all integer values of δ within 0–10, resulting in a Pareto frontier between model objectives for each one of the supply scenarios considered, or between CO₂ emissions and the cost of chain management incurred to achieve said emission levels (Figure 2).

Independently of the scenario considered, a higher cost implies a lower quantity of CO₂ emitted. Further, each scenario's Pareto frontier behaves similarly. For mean values of δ , the chart is practically linear, but on the ends, a change in the slope is shown, which results in each curve presenting upward concavity. This behavior on the ends for large δ values (left end of the curves), is a result of low or null subcontracting, and as such, a simple rescheduling of the association's vehicles allows them to achieve important changes in the quantity of CO₂ emitted, with little additional cost. However, for small δ values (right end of the curves), to guarantee a low level of emissions, all routes and collections from individual producers are subcontracted, and, as such, there are few options for vehicle rescheduling. This implies a considerable increase in cost, when compared to the minimal reduction in emissions.

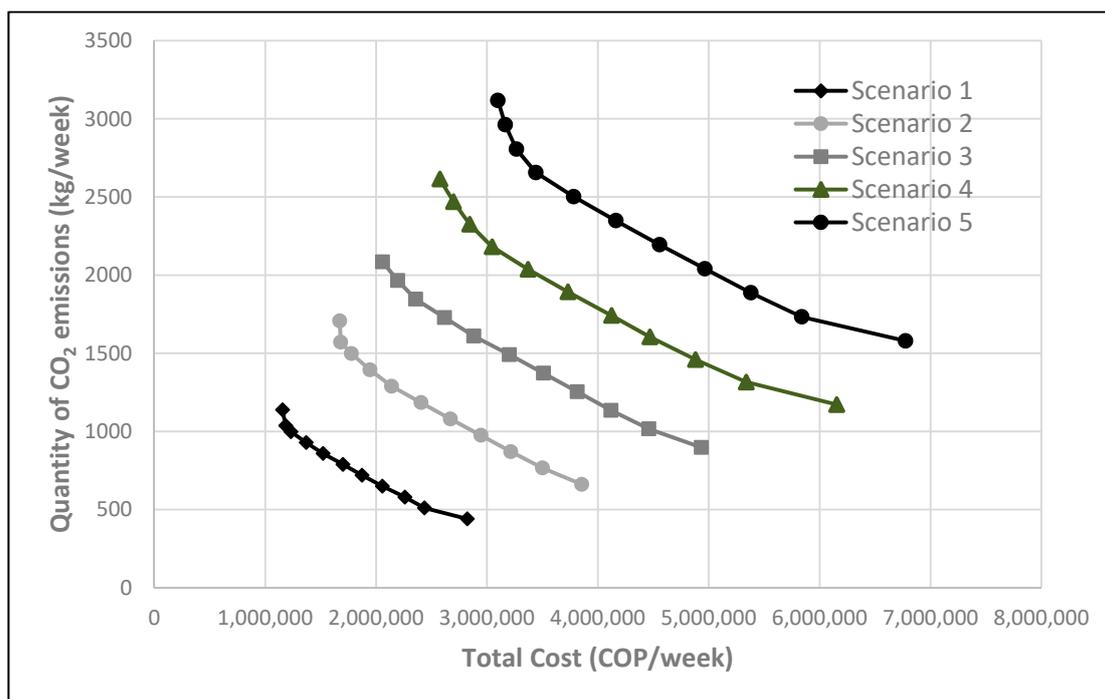


Figure 2. Relationship between total cost and quantity of CO₂ emissions.

Clearly, the principal variable that affects total cost as well as the quantity of emissions is supply, which displaces the Pareto frontier. Figure 2 shows the way in which, as supply increases from Scenario 1 to Scenario 5, the charts move positively, and, for each curve, a greater difference between the ends thereof is presented, i.e., the curve elongates. On the one hand, the motive for the movement of the frontier is evident, given that costs and emissions are directly proportionate to supply. On the other hand, the curve elongates with the change of scenario, given that greater supply increases vehicle scheduling leeway, thus maintaining the objective of minimum cost achievement. For example, greater supply implies that the collection–distribution process may be redistributed to other days of the week without incurring excessive cost increases when transporting near capacity each day. For scenarios of low supply, this would not be possible, as making use of additional days would mean sending vehicles with little cargo, which would go against the objective of minimizing total cost. Said increase in leeway, then, absolutely causes emissions to be further reduced, and, as such, costs reduce also.

However, in a relative sense, the behavior is not the same, as observed in Figure 3 Pareto frontiers. This shows that the differences between scenarios are not as pronounced when the cost is measured as an increase of the minimum of each scenario, and the quantity of emissions is measured as a percentage of the maximum of each scenario. For example, Scenarios 1 and 2 present the greatest relative CO₂ emission reductions, but Scenario 2 does so with a lesser cost increase (39% of emissions in both scenarios, with a cost increase of 144% in Scenario 1, and 130% in Scenario 2).

This behavior shows that there is no relationship between the supply of fruit and the increase in total cost, which is corroborated in Figure 3, as it does not present a natural order, as observed in Figure 2. Only for $\delta = 0$ (right end of the curves), with the exception of Scenario 2, it is observed that greater supply (Scenario 5) implies a lower increase in cost (119%) and vice versa (see Scenario 1). Said behavior is inverse to that shown in Figure 2. This means that, if supply is kept constant, a high cost could be reduced a great deal, in terms of COP, but not so much in terms of percentage. Likewise, a low cost can be reduced minimally in terms of COP, but a bit more in terms of percentage.

Similarly, there is no relationship between the supply of fruit and the relative quantity of emissions, with the exception of the case in which $\delta = 0$, in which an inverse supply-quantity of emissions

relationship is presented as a percentage of the maximum. For example, for Scenario 5 (that with greatest supply) emissions may be up to 51% of the maximum, while in Scenario 4, they may be 45%, and in Scenario 3, 43%. This means that, in general, important reductions in the levels of CO₂ emissions can be achieved just with vehicle rescheduling, which implies an increase in costs associated purely with the collection–distribution process, but investment in additional technology would be unnecessary.

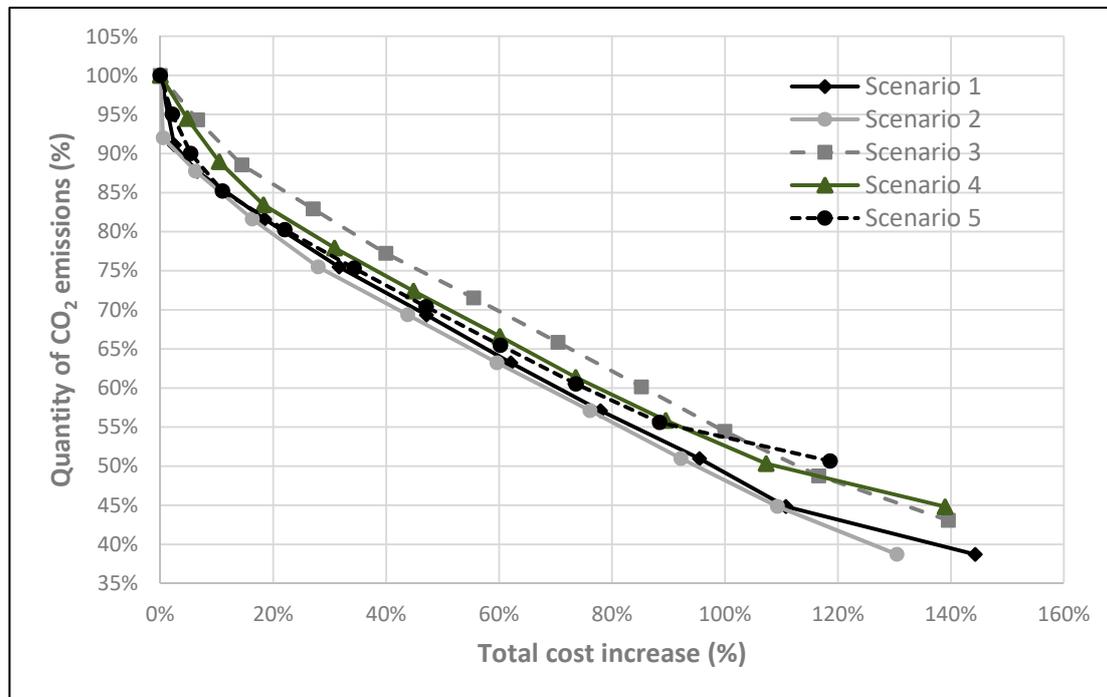


Figure 3. Relationship between total cost increase and the relative quantity of CO₂ emissions.

6. Conclusions

The present investigation addressed a tactical problem, which was modeled in a supply chain for the collection and distribution of fruit from producers in the countryside to retail customers. In an academic environment, the main contribution of this study is in the analysis of a supply chain through the design of a multi-objective mixed-integer programming model. This model includes decisions about quantities of perishable product to be transported and stored, the number of trips to be made to different links in the chain for vehicles with diverse capacities, use of existing collection centers, subcontracting decisions, and vehicle CO₂ emission levels. All of these decisions must be made from Monday to Friday, given weekly supplies. In the practical scope, the main contribution of this study is in the creation of a plan for weekly vehicle scheduling for the fruit producers Association, which minimizes the total cost of chain management and CO₂ emission levels.

Five supply scenarios were considered, based on real data in which, initially, the objective of minimizing CO₂ emissions was not considered. The results of these test runs revealed a collection–distribution plan for each scenario, each day of the week, in which the use of vehicles with greater capacity (6000 kg) was much greater than use of 1500 kg vehicles, independently of the scenario or link in the chain. Additionally, it is not necessary to subcontract any point or collection route, as the Association’s vehicles provide a sufficient weekly capacity, without the need to incur additional costs. This plan provides the absolute minimum cost for each scenario, as non-restriction of emissions may achieve the minimal cost goal. Thus, if the fruit producers Association decides to implement this plan, they should schedule vehicles as described in this article. It is suggested that the Association previously design a forecast model, which would allow them to determine,

with the greatest possible precision, the supply of fruit that may be available, and thus schedule collection–distribution in accordance with that information.

Later, CO₂ emissions were minimized using the ϵ -constraint method [54], in which emissions are limited through the addition of constraints to the model. Said procedure increased weekly management costs, principally owing to a greater use of 1500 kg vehicles than 6000 kg vehicles. Although the former emits less CO₂ per unit of cargo transported and unit of distance covered, their use is costlier, not only per unit of cargo, but also because a greater number of trips must be made to maintain collection and distribution of 100% of the fruit. Secondly, the cost of management also increases, owing to the subcontracting of collection on routes and for individual producers. The representation of the cost of subcontracting in the total cost depends on the scenario considered, and on the limit established in the emissions. However, in the scenario in which this is greater, it presents a maximum of just 17%. Despite this, it is suggested that future investigations include the quantity of subcontracted vehicle emissions, although their cost impact can be minimal.

Finally, although a Pareto frontier was established which shows a general relationship between the quantity of CO₂ emissions being inversely proportional to management cost, it was observed that supply affects this relationship. For future studies, then, the effect of other variables, such as loading and unloading times, use of less contaminating vehicles (which could include decisions about technological investment within the model), traffic in the urban distribution, and the state of roads in the collection chains should be incorporated. In these rural areas, many roads are not paved, and are affected by rain, heavy vehicle traffic, or during intense drought, by the dust generated, which impedes visibility. A tactical-operative or purely operative study could be carried out to consider all of these variables. Additionally, the model could consider that the real supply of fruit is random, and, as such, a study could be carried out which considers the robustness of the schedule designed.

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