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Supply Chain Network Design of Perishable Food in Surplus Periods

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ABSTRACT

Research on the design of the perishable food supply chain network has increased in recent years. However, little attention has been given to those seasonal foods that generate periods of oversupply and, particularly, to their impact on the sustainability of small producers in developing countries. This research proposes and develops a multi-objective mixed linear programming model for perishable fruits in a south American country at oversupply periods. It minimizes losses and transportation costs and maximizes the inclusion of farmers. It considers four echelons of the supply chain: farms, collection centers, distribution centers and the demand, which is represented by the agroindustry, wholesalers, shopkeepers, and hypermarkets. The Epsilon constraint method is used to solve the multi-objective model. A set of Pareto optimal solutions helped evaluate tradeoffs between the three objectives and find the location of collection and distribution centers. The proposed generic mathematical model is applicable to any food supply chain, as it allows for the improvement of the established performance measures and the distribution flows for the different echelons. The model considers the losses in perishable food from the impacts caused by changes in temperature (T^0) and humidity level (RH) at different thermal floors of mountain ranges.

Keywords: *Multi-objective model; collection-wholesale centers; perishable fruits; farmers; shopkeepers.*

1 Introduction

Supply chain network design is determined by its configuration, which derives from the location of the production, collection, transformation, storage, trade and distribution facilities, as well as the intensity and frequency of food flows between them (Orjuela-Castro, Orejuela-Cabrera, and Adarme-Jaimes, 2021). The food supply chains of agricultural products include a set of growers, processors, wholesalers, importers and exporters, retailers and specialty stores (Van der Vorst, Da Silva, and Trieneken, J., 2007; Ahumada and Villalobos, 2011), input suppliers, logistics services, public institutions and unions (Orjuela Castro and Adarme Jaimes, 2017), infrastructure for public or private transport, and storage (Argenti and Marocchino, 2007).

The demand for fresh food is increasing; nevertheless, in the perishable food supply chain (PFSC), there is a constant change in the quality of the food from the grower to the consumer, which generates losses and makes logistics difficult (Orjuela-Castro, Sanabria-C, and Peralta-L, 2017). Some studies show losses of up to fifty percent (WFPC LLC, 2014), which affects the stakeholders of the PFSC — mainly the producers. For perishable food supply chain network design (PFSCND), quality, shelf life, safety, supply uncertainty, climate variability, prices and low margins are important (Orjuela-Castro, Orejuela-C, and Adarme-Jaimes, 2019; Orjuela-Castro, Orejuela-C, and Adarme-Jaimes, 2021). Food supply chain in some developing countries with mountain ranges use inadequate means of transport, then generate a big loss of perishable food due to changes in relative humidity (RH) and temperature (T^o). Furthermore, the seasonality of some foods generates oversupply seasons reducing the price, which affecting small scales farmers.

To identify a more efficient supply chain design, It is necessary to develop models that represent the different features of the food supply chain, as well as including objective functions that improve performance of the PFSC. When the model is a multi-objective optimization model, the search for solutions is often complex (Goetschalcka, Vidal, and Dogan, 2002). Then the question emerges: what is an improved supply chain network design for perishable food in countries with mountain ranges and inadequate transport (not refrigerated), so that perishable food losses and logistics costs decrease, while the inclusion of farmers increases in surplus periods?

This document has been organized in four parts: the literature review; the research methods, where the research problem is presented; the model formulation and the case study. Section four shows the results and discussion, followed by the conclusions.

2 Literature Review and problem statement

Different food supply chain network designs carry levels of provisioning, collection, transformation, storage, distribution and transportation (Akkerman, Farahani, and Grunow, 2010), as well as different delivery times, qualities and deterioration (de Keizer, Akkerman, Grunow, Bloemhof, Haijema, and van der Vorst, 2017). Several measures of performance for the PFSC have been proposed: the response capacity is proposed by Bigliardi and Bottani (2010), shelf life and quality by Aramyan, Ondersteijn, van Kooten, and Lansink (2006), and losses due to logistics management (Orjuela-Castro and Adarme-Jaimes, 2018). Authors such as van der Vorst, van Kooten, and Luning (2011) and Yu and Nagurney (2013) have found that PFSC models don't include supply, trade, or consumption.

Food safety is affected by the supply-demand balance on PFSCs. Food security is achieved when the availability, access, quality and quantity required by the population is attained (IICA-PRODAR, FAO., 2009; CISAN-ICBF, 2013; Chukwudum and Dioggban, 2022). Regarding the vulnerability and resilience of food systems, there are differences between countries according to their level of development (Stave and Kopainsky, 2015), growth in consumption, production, market, price and income (Ayenew and Kopainsky, 2014). In times of high production or oversupply, the prices fall, then the producers do not recover production costs. In this context, the optimization model has been used to model the PFSCND. Its application allows the optimal location of the facilities to be established, as well as determining flows in the chain, which together establish better performance measures (Orjuela-Castro and Adarme-Jaimes, 2018).

There are studies about how to make producers more efficient through strategies such as the formation of clusters (Bosona, Gebresenbet, G., and Gebresenbet, 2011) for producers who are spatially near (Clark and Inwood, 2016), or through the improvement of transport, infrastructure, collection centers or food processing plants (Johnson, Nketia, and Quaye, 2015). In European countries, short food chains, such as direct sales, are promoted along with quality processes and organic agriculture, where the identification of origin is carried out with traceability systems (Renting, Marsden, and Banks, 2003; Herrera and Orjuela-Castro, 2021; Otero-Diaz, Orjuela-Castro and Herrera, 2021).

The production of seasonal perishable food has periods of high and low supply which leads on oversupply and shortage periods, while the demand remains practically constant (Orjuela-Castro, Diaz G, and Bernal C, 2017). Farmers operate with high transport costs and high losses added to low food prices in times where there is oversupply. Consequently, small-scale farmers become disinterested in food production which puts food security at risk (Orjuela-Castro, Orejuela-C, and Adarme-Jaimes, 2019). Many farmers switch to biofuel production (Orjuela-Castro, Aranda-Pinilla, and Moreno-Mantilla, 2019). This raised the following question: how will agricultural smallholdings be preserved, particularly in times of production surplus, to ensure food safety?

One way to improve the performance of the PFSC is by redesigning its network (PFSCND) (Orjuela-Castro, Orejuela-Cabrera and Adarme-Jaimes, 2022). The PFSCND presents challenges, such as multiple decisions, objectives, levels, periods and a lot of stakeholders (Miranda-Ackerman, Azzaro-Pantel, and Aguilar-Lasserre, 2017). There is a lack of representativeness in existing theoretical models of the behavior of reality in the PFSC (Goetschalcka, Vidal, and Dogan, 2002), (Novaes, Lima Jr, Carvalho, and Bez, 2015). The use of integrated approaches and models in PFSC is limited; the models don't incorporate their attributes, such as the incidence of the cold chain, shelf life, organoleptic characteristics, harmlessness or freshness (Soto-Silva, González-Araya, Oliva-Fernández, and Plà-Aragonés, 2017). Thus, indicators should be used to assess the performance of the PFSC, such as efficiency, responsiveness, quality (Manzini and Accorsi, 2013), as well as the permanence of supply chain stakeholders on the market.

There is little research that studies the reduction of food losses as a strategy to improve food availability in south American countries (Yared Lemma and Gatew, 2014). The supply chain models in existing literature don't include stakeholders such as farmers, retailers, supplier, and wholesale centers (Utomo, Onggo, and Eldridge, 2017).

In summary, a review of existing literature shows the lack of studies that contemplate supply chain network design for perishable foods in surplus periods, where the impact on small producers, losses and transport costs in developing countries with mountain range environments, considering relative humidity and temperature, are evaluated. This is the research problem that has been studied.

3 Research Methods

3.1 Model Elements

Perishable food supply with seasonality generates periods of oversupply or shortage. This investigation addresses the first case, oversupply. For this, the supply chain network design is modified and three objective functions are raised: minimization of losses, reduction of transport costs and maximization of the number of farmers involved. Reduction of losses is achieved when intermediate points are increased, as consolidation processes prevent losses and improve packaging and transport conditions. This, in turn, improves the level of service that can be achieved, with less loss, greater consumer satisfaction, supply and availability, as well as better organoleptic and biophysical characteristics and, therefore, better food quality.

Transport costs increase as intermediate nodes are added, so the reduction in the number of intermediate nodes is sought. The distances covered by perishable food have increased, leading to the need for more distribution centers. In turn, the handling costs of loading and unloading will be increased. The farms use small vehicles because of the characteristics of the land, without scale benefits in transport, while scale economy is achieved in the collection centers (CC) and wholesalers (WS). The high cost of transport affects the aperture of the CC by encouraging direct trips, thus presenting a positive connection with the following performance measures: supply times, transport times, dispatch times, and inventory costs.

Maximizing the number of farmers is important in times of food oversupply. If only cost is considered, the model excludes farmers for reasons of distance. If only loss is contemplated, the model will take out those farmers that, for reasons of altimetry, incur greater losses due to T^0 or RH. In both cases, the two performance functions would generate a monopoly between the best located producers, which, in the long term, discourages the offer of other farmers, and with it, variety and quantity. Therefore, to maximize the number of farmers, the model will try to activate all producers with a minimum load, as it is an important element in food sustainability that the exclusion of farmers should be avoided through programs that allow their development in the long term.

For the construction of the model, a review of the literature on location models in FSC was carried out (Sanabria C, Peralta L, Orjuela-Castro, and Javier, 2017). From this review the variables, parameters, objective functions and constraints used by researchers in location models were identified. Based on this and the characteristics of the PFSC, the multi-objective model for localization was developed. With this model a region of efficient border could be established for the strategic decision making of the PFSC stakeholders and the configuration could be established. Unlike the mono-objective model (Orjuela-Castro, Sanabria-C, and Peralta-L, 2017), which is used as the reference, the multi-objective model developed in our research considers overage stocks in the nodes, including the initial node, which generates the dispatch from the farms or a penalty. The model considers the perishability, including the loss caused by over handling on storage, as well as loss caused by changes to relative humidity (RH) and temperature (T^0) due to trips through different thermal floors.

3.2 Model Formulation

The model determines the location of the collection centers in Cundinamarca and of wholesalers in Bogotá Colombia. They are represented by nodes, each representing a municipality, agroindustry, marketplaces, hypermarkets or shopkeepers (Figure 1).

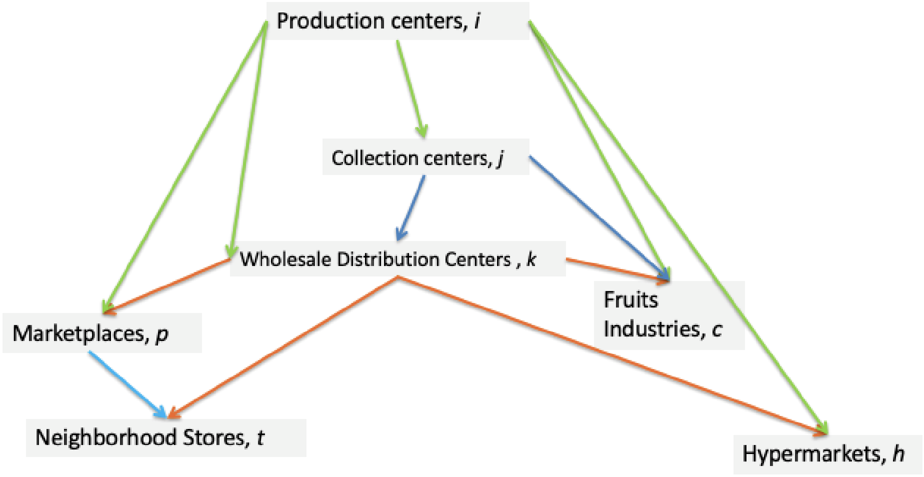


Figure 1. Localization graph model.

In the context of the problem being considered in this paper, it is necessary to guarantee the balance in each of the echelons of the supply chain. However, as the problem considers that the supply exceeds the demand, for each of the echelons the possibility of having oversupply is established. Therefore, to make the flow balance in every production center and for every food available (*f*), the model will be forced to send the demand (*d*) to all selected nodes, otherwise there will be an oversupply at the production center (*PC i*). On the other hand, for flow balance in each collection center (*CC j*) or wholesaler center (WC k) for every food (*f*) received, it is necessary that the quantity of each perishable food (*f*) for all (*PC i*) and all (*CC j*), is equal to the amount of food that leaves *j* towards all possible *k* or *j* destinations. The excess that remains in *k* or *j*, must also take into account the loss caused by changes to RH and T^0 in the different nodes and flows between all echelons of the PFSC.

Another important aspect regarding the balance has to do with demand which, for all final customers (*FC*), Industries fruits (*c*), Neighborhood Stores (*t*), Marketplaces (*p*) or Hypermarkets (*h*), is to establish the proportions of the demand satisfied by each of the possible suppliers (*PC*, *CC*, and *WS*). Hence, it is necessary that food sent by the *PC, CC* or *WS* to every *FC* be enough, including the excess food defined for each *FC*. The losses between the origins to the destinations and in storage at *FC should also be considered*. Note that this model generates a reconfiguration of the logistics network, since there are already *CC* and *WS* located at defined geographical points, which implies that it will be decided whether a node is opened or closed, or if it will be used for another food logistics network.

The formulation includes the parameters, decision variables, constraints (demand balance, flow, and capacity), objective functions and sets. The most important elements of the model are shown below (see Appendix A for more details).

Sets:

$F = \textit{Types of perishable foods, index } f$

$C = \textit{Centers of productive transformation, index } p$

$H = \textit{Hypermarkets, index } h$

$I = \textit{Production centers, index } i$
$J = \textit{Possible location areas for colletion centers index } j$

$K = \textit{Possible location areas of wholesale centers, index } k$

$P = \textit{Market places, index } p$

$T = \textit{Consolidated stores, index } t$

$OT = \textit{Set of all possible origins, index } o\ , OT = (I \cup J \cup K)$

$DTOT\{o\} = \textit{Possible destinations of origin } o \in OT$

$FOT\{o\} = \textit{Set of perishable food types that can be sent by the origin or } \in OT$

$FDT\{d\} = \textit{Set of types of perishable food that can be received at the destination } d \in DT$

$DT = \textit{Set of all possible destinations, index } d, DT = (J \cup K \cup P \cup T \cup H \cup C)$

$DI = \textit{Set of intermediate and final destinations, index } d3, DI = (K \cup P \cup T \cup H \cup C)$

$FDI\{d3\} = \textit{Set of types of perishable food that can be destined for } d3 \in DI$

$ODF = \textit{Set of all arcs origen} - \textit{destination } (o, d) \textit{ that can movilaze the fruit } f$

$\mathrm{DD} = \textit{Set of all arcs between nodes intermediate and final destinations } (d, d3) \textit{ that can movilaze the fruit } f$

Index j in J

k in K

(o, d, f) in ODF

(d, d3, f) in DD

i in I

Parameters:

$HN_{od} = \textit{Percentage of loss due to change in relative humidity between origin } o \in OT \textit{ and destination } d \in DTOT\{o\}.$

$TN_{od} = \textit{Loss percentage due to temperature change between the origin } o \in OT \textit{ and the destination } d \in DTOT\{o\}$

$\beta_{fd} = \textit{Percentage of storage waste in the destination of } DT \textit{ of the type of perishable food } \in FDT\{d\}$

$CF_j = \textit{Fixed cost of the colletion center located in } j$

$CG_k = \textit{Fixed cost of the wholesale center located in } k$

$CT_{od} = \textit{Transport cost between the origin } o \in OT \textit{ to the destination } d \in DTOT\{o\}$

$DIN_{od} = \textit{Distance between the origin } o \in OT \textit{ and destination } d \in DTOT\{o\}$

Variables:

$$BPI_i = \left\{ \begin{matrix} 1 & \textit{if the Production center } i \in I \text{ is considered} \\ 0 & \textit{On the contrary} \end{matrix} \right\}$$

$$X_j = \left\{ \begin{matrix} 1 & \textit{If a collection center is opened in the area } j \\ 0 & \textit{On the contrary} \end{matrix} \right\}$$

$$Y_k = \left\{ \begin{matrix} 1 & \textit{If a wholesale centeris opened in the area } k \\ 0 & \textit{On the contrary} \end{matrix} \right\}$$

$W\mathrm{N}_{fod} = \text{Amount of the type of perishable food } f \textit{ to send from } O \textit{ to } D \textit{ with } \forall\, O \in OT,\ \forall\, D \in DT, \forall\, f \in F$

Objective Function:

$$\text{Minimize Z} = \text{F}(\text{OBJ1}, \text{OBJ2}, -\text{OBJ3}) \tag{1}$$

The problem considered is multi-objective: on one hand, it seeks to minimize the total waste product of the flows in the chain; on the other hand, the minimization of variable transport costs is sought and, finally, it seeks to maximize the number of farms involved in the process.

Constraints associated with the objectives:

Minimization of total waste: This considers the loss of fruit due to material handling in the storage nodes, temperature changes and relative humidity changes between the origins and destinations of the flows.

$$\begin{aligned} \text{OBJ1} = \text{MIN Z1} = & \sum_{(\text{o,d,f})} \text{WN}_{\text{fod}} * (\text{TN}_{\text{od}} + \text{HN}_{\text{od}}) + \\ & + \sum_{(\text{d,d3,f})} \text{WN}_{\text{fdd3}} * \beta_{\text{fd}} \end{aligned} \tag{2}$$

Minimization of transportation and opening costs: This considers the fixed cost of operation of the collection and wholesale centers and the cost of transporting the flows between the arcs.

$$\text{OBJ2} = \text{MIN Z2} = \sum_{\text{j}} \text{X}_{\text{j}} * \text{CF}_{\text{j}} + \sum_{\text{k}} \text{Y}_{\text{k}} * \text{CG}_{\text{k}} + \sum_{(\text{o,d,f})} \text{WN}_{\text{fod}} * \text{CT}_{\text{od}} * \text{DIN}_{\text{od}} \tag{3}$$

Maximize the number of suppliers considered in the process: This seeks to ensure that the largest number of producers or agricultural areas participate in the production process.

$$\text{OBJ3} = \text{MAX Z3} = \sum_{\text{i}} \text{BPI}_{\text{i}} \tag{4}$$

Equation (1) represents the multi-objective function which is developed in the following equations: Equation (2) represents the waste that occurs during transportation due to the change of T^0 and RH and the loss of food due to handling during storage is represented. Equation (3) represents the transportation costs of the different flows and the fixed opening costs of the CCs and the wholesale DCs. Equation (4) represents the objective associated with guaranteeing availability, ensuring that the greatest number of producers can sell their fruits in such a way that competences are developed among all, to avoid a monopoly being reached due to producers closer to the demand benefiting. The rest of the functions are found in Appendix A, in which constraints from (5) to (7) are related to the production areas; they control the flow balance, the opening control, and the minimum flow respectively. Constraints (8) and (9) are responsible for the flow balance and capacity control and opening of the collection plants. Constraints (10) and (11) are responsible for the flow balance and capacity control and opening in wholesale distribution centers (WS). Constraints (12) to (14) are responsible for meeting the levels of demand for each of the echelons. Constraints (15) to (17) ensure that there are no flows to and from any of the unopened echelons. Constraints (18) to (27) are to guarantee the type of variables and their domain (See formulation details in Appendix A).

3.3 Case study: Perishable Fruit Supply Chain

As of 2020, Cundinamarca has 3,225,000 inhabitants, the fourth highest population of Colombia, while Bogotá is the capital of the country with 7,901,553 inhabitants as of 2022. Cundinamarca has 116 municipalities in a region of 24,210 km². Cundinamarca is located in the center of the country, in the Andean region of the eastern mountain ranges. Thus, it has a diversity of thermal floors and is a producer of a wide variety of foods. The department supplies food to the capital, meeting 60% of the capital´s demand (Orjuela Castro, Caderón, and Buitrago, 2006). Bogotá is located in the center of the Cundinamarca; it has 20 locations and covers 1,775 km^2.

A general model for the perishable fruit supply chain (PFrSC) is obtained. The research proposal evaluates the PFrSC for five fruits (specifically blackberries, strawberries, mangos, tangerines and oranges) in the region of Bogotá, in

Cundinamarca, Colombia. The multi-objective optimization model was applied during the design of the PFrSC to define where the collection centers and distribution centers must be located, as well as to determine the flows between the nodes.

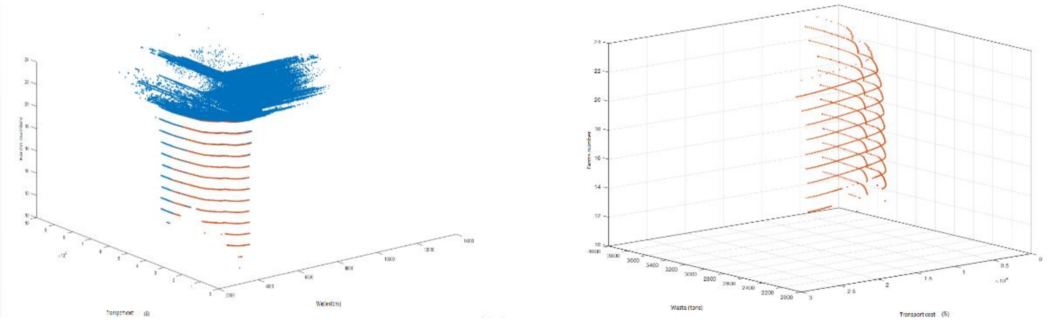
For parameterization of the model, official statistics of national, multilateral, governmental and trade institutions were analyzed. Guilds and institutions databases, (EVA) -Agronet, FAO and WTO consumption and TRADE-MAP were also used (Ensin, 2005; Ensin and Minsalud, 2010; Ensin and ICBF, 2015). The above information was complemented with surveys completed by the stakeholders of the PFrSC between 2014-2017. We considered 763 surveys from the perishable fruit supply chain stakeholders, farmers, transporters, agribusiness, hypermarkets, shopkeepers, and marketplace merchants. From the surveys, the input data of the different echelons was obtained, and we were also able to parameterize the model. The parameters associated with the loss of fruit due to handling in the storage nodes, changes in temperature and changes in relative humidity are based on the research of Orjuela-Castro, Sanabria-C and Peralta-L., 2017.

4 Results and discussion

The supply chain for the five fruits examined in this study were chosen as they have the highest production. The oversupply model was applied to the perishable fruits supply chain for 24 of the 54 municipalities of Cundinamarca as these municipalities produce the five fruits identified.

4.1 Pareto Borders

To obtain the Pareto border, 250,000 runs were performed in AMPL for each objective function, applying e-constraints. The total variables were 2,401,33 binary and 2,368 linear, with 422 constraints from equality and 1,514 from inequality. The solutions were obtained through Gurobi 7.5.0. For the first objective, 177 simplex iterations, 1 branching and dimension node and more than 1,041 internal base simplex iterations were used. For the second objective, 772 simplex iterations, 6 branching and dimension nodes and more than 1,353 iterations of simplex interior base were used. For the third objective, 428 simplex iterations, 1 branching and dimension node and more than 579 internal base simplex iterations were used. Figure 2 shows the results of the three objective functions (minimization of costs, minimization of losses and maximization of producers included municipalities), as well as the Pareto border (in orange), which were obtained by means of the non-dominance technique.



Borders obtained in the 750,000 runs.

Efficient Pareto Borders, 5,440.

Figure 2. Pareto Borders.

The optimal values for the proposed objective functions have been highlighted in yellow (4.2 Derived
Configurations

Given that there are 5,440 non-dominated points that form the efficiency frontiers, there would be the same number of triples of the performance measures, each giving rise to a possible configuration. Therefore, the configurations at the extremes were obtained. The extreme point is where every objective was optimal and a fourth objective in search of the balance between the three measures of performance was also considered. The purpose of this is to give different options for decision-making to the stakeholders. To determine the latter, the mean value taken by the objectives at the efficiency frontier was found when applying e-constraints. The closest point to the mean value that was not dominated was chosen. The configurations correspond to the lists found in **Fehler! Ungültiger Eigenverweis**

auf Textmarke.. The three objectives generate different locations for the collection and distribution centers (wholesalers). Table 2 presents the collection and distribution centers open for each configuration.

Table 1). The tradeoff between the three shows that the decisions to be made depends on the performance measure for which optimization is sought, or how a balance between the three is achieved.

4.2 Derived Configurations

Given that there are 5,440 non-dominated points that form the efficiency frontiers, there would be the same number of triples of the performance measures, each giving rise to a possible configuration. Therefore, the configurations at the extremes were obtained. The extreme point is where every objective was optimal and a fourth objective in search of the balance between the three measures of performance was also considered. The purpose of this is to give different options for decision-making to the stakeholders. To determine the latter, the mean value taken by the objectives at the efficiency frontier was found when applying e-constraints. The closest point to the mean value that was not dominated was chosen. The configurations correspond to the lists found in **Fehler! Ungültiger Eigenverweis auf Textmarke.**. The three objectives generate different locations for the collection and distribution centers (wholesalers). Table 2 presents the collection and distribution centers open for each configuration.

Table 1.
Optimal of the three objective functions.

Objective function	Min OBJ1	Min OBJ2	Max OBJ3
BJ1: Minimize losses (hundreds of dollars)	2.16	290.8	15
BJ2: Minimize transport costs (tens of thousands of millions of dollars)	3.88	36.2	13
BJ3: Maximize availability (number of municipalities producing)	13.2	968.6	24

Figure 3 shows the flows between the different stakeholders of the warm-weather PFrSC, for the three objectives and for the mean of the three objectives. The intensity of flow is reflected in the thickness of the arches. The flows are greater among agricultural producers (*AP*), collection centers (*CC*) and wholesale centers (*WC*) in objective 2 (efficiency), followed by objective 1 (quality) where the flow has the same behavior but in smaller quantities.

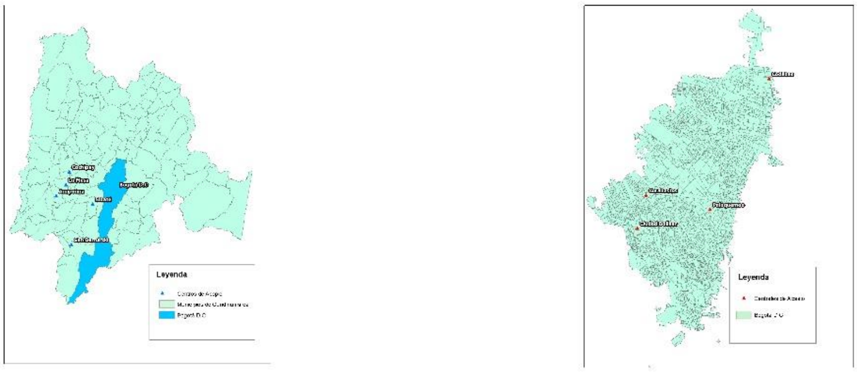
Table 2.
Locations of collection and distribution center, surplus case.

Open Collection Centers			**Open Wholesale Distribution Centers**		
Localization	Min. Objective BJ1, Max. Objective BJ3	Min. ObjectiveBJ2 with the Mean of the Objectives	Localization	Min ObjectiveBJ1 Min ObjectiveBJ2 With the Mean of the Objectives	Max Objectives BJ3
Anapoima (25)	25	25			
Cachipay (26)	26	26	Codabas (31)	31	NC
La Mesa (27)	27	27	Ciudad Bolívar (32)	32	32
Tocaima (28)	NC	NC	Corabastos (33)	33	33
San Bernardo (29)	NC	29	Paloquemao (34)	34	NC
Sibate (30)	30	30			

NC: Not Chosen

OBJ1, OBJ3 *CC* in Cundinamarca

OBJ3 *WC* in Bogota



OBJ2 *CC*, OBJ CC mean *CC* in Cundinamarca

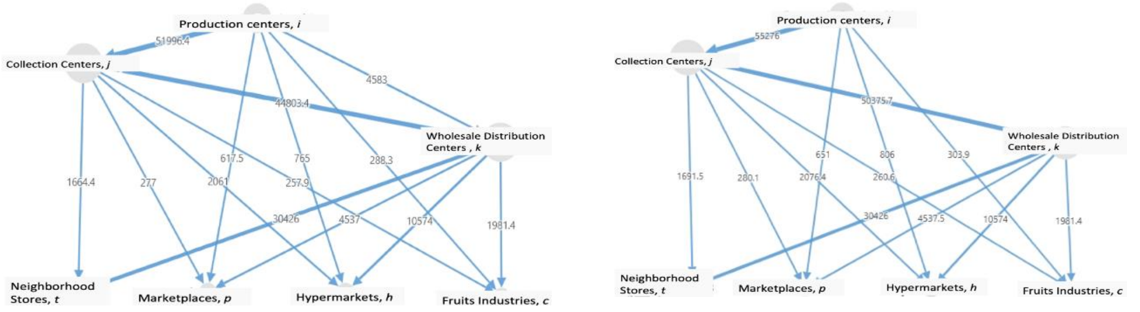
OBJ1, OBJ2, OBJ mean *WC* in Bogota

Figure 3. Collections Centers (CC) and Wholesale Center (WD).

Figure 4 shows the flows between the different stakeholders of the warm-weather PFrSC, while in figure 5, shows the flows between the different stakeholders of the cold-weather PFrSC. The solution of the model for the five fruits considered in this study is that the producers prefer to send produce to the *CC* from where they are delivered directly, without going through the *WS*, where the amounts identified by objective three (maximization of participating municipalities) are greater that the first two objectives.

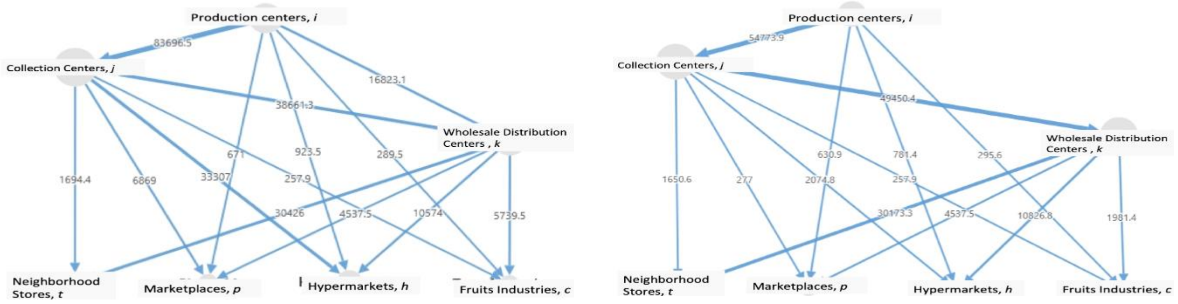
4.3 Discussion

The multi-objective optimization model designed for the PFrSC allowed us to show different configurations of the supply chain. Its application allows us to establish that the stakeholders can move to more efficient borders for the established performance measures: minimization of transport losses and costs, and the maximization in participation of producers in times of surplus. However, tradeoffs between these objectives are presented. The configuration at a strategic level when establishing the location of collection center facilities in fruit production regions and wholesale centers for urban consumption is considered. An appropriate configuration of the PFrSC generates a cost dimension that can move volumes, achieving economies of scale. If adequate logistics, transport and specialized warehouses are also included, the losses will be reduced and efficiency will increase (Cote Polanco and Orjuela-Castro 2021). For its part, the use of intermediate nodes must be guaranteed, which allow the orders consolidation as well as food preservation and improvements to the performance of the Perishable Fruit Supply Chain.



Objective 1: Loss minimization

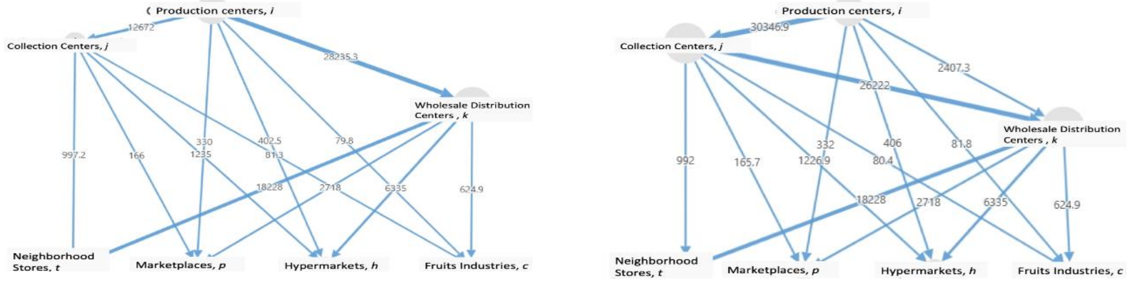
Objective 2: Minimization of transport costs



Objective 3: Maximization of the municipalities participating

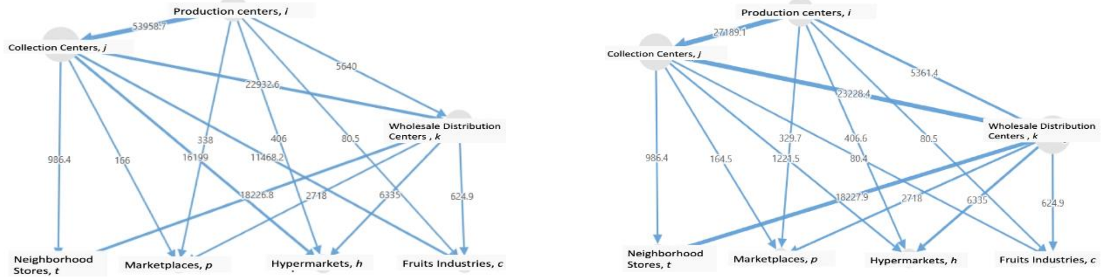
Combining the mean of the three objective functions

Figure 4. Objective-based flows, warm-weather fruits.



Objective 1: Loss minimization

Objective 2: Minimization of transport costs



Objective 3: Maximization of the municipalities participating

With the mean of the three objectives

Figure 5. Objective-based flows, cold-weather fruits.

In times of oversupply, the prices of fruit at the time of selling can be so low they do not even cover costs, affecting the farmers. However, the consumers benefit as the low prices increase access. In surplus periods, farmers can put availability at risk as production is discouraged. The effect of seasonality on food security is evident here. Therefore, it is imperative to look for mechanisms that mitigate or reduce these effects. Some options in times of surplus are government food programs, such as food banks, and the participation of the state, as the state can buy fruits at the source (the farm), so that farmers can recover their minimum costs. Other possible solutions are stimulus to demand, so that when there is oversupply, consumers increase their consumption of healthy foods. Government support to improve exports with the existing free trade agreements would also ease the pressure. Another possible path is to develop fruit transformation systems in regions of origin to develop processed products that do not perish quickly, such as pulps or juices.

In multi-objective models, Pareto borders are available as performance measures, as there are multiple non-dominated solutions. Thus, government institutions, the guilds, unions and PFrSC stakeholders, would decide what the best configuration is, evaluating the three objectives based on their interests. This is because each stakeholder has assorted interests and, therefore, make decisions based on different performance measures, with different prioritization, depending on the stakeholders prioritization of the performance measures, the respective trade-offs will be found. In such cases, a good solution based on the mean from the objectives is obtained. Authors such as Soto-Silva, Nadal-Roig, González-Araya, and Pla-Aragones (2016) have stated that there is a lack of models that better represent reality. Our model include the effects of RH and T^0 on food losses due the thermal floors, as well as the means of transportation used in mountainous regions.

Bosona, Gebresenbet and Gebresenbet (2011) showed the need to keep small farmers as competitors in the field and avoid monopolies. This research contributes to the literature, as it maximizes the participation of small producers in times of fruit oversupply. In developing countries, the diversity of producers leads to better availability and consequently contributes to food security. The multi-objective and multilevel model designed includes all the echelons of the PFrSC: farmers, agroindustry, supply and distribution centers, neighborhood stores, marketplaces and hypermarkets.

5 Conclusions

A multi-objective model MIP for the Perishable Food Supply Chain (PFSC) has been developed for times of surplus, validated in the case of the Perishable Fruits Supply Chain (PFrSC) for cold- and hot-weather fruits. The model includes loss minimization, transportation costs and maximization of farmers inclusion.

The consideration of multiple objectives in the configuration of the network of a PFSC allows us to generate a set of solutions. Nevertheless, the stakeholders must make decisions based on the best performance according to their interests. In this research, the extreme efficient solutions for each objective are presented and an analysis of these versus a solution that seeks balance between the different performance measures is carried out. In that context, it is common to find tradeoff decisions.

The model approaches real problems by including climatic characteristics in a mountainous environment, where T^0 and RH affect food losses when non-specialized vehicles are used for food transportation, as is the case in developing countries.

The model can be used by the different stakeholders in the chain; however, given that tradeoffs are presented, the unions, government agents and stakeholders of the chain must sit down for decision making, which can be supported with other techniques, such as multi-criteria or multi-goals.

We proposed that future research includes parameters, especially for demand. It is proposed that an income function that considers the effect of prices and their relationship with oversupply is explored.

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Appendix A. Mathematical Model

A.1 Sets

$DF = Set\ of\ final\ destinations, index\ d2, DF = (P \cup T \cup H \cup C)$

$DFF\{f\} = Set\ of\ final\ destinations\ that\ can\ receive\ the\ types\ of\ perishable\ food\ \ f$

$DIF\{f\} = Set\ of\ intermediate\ and\ final\ destinations, which\ can\ receive\ the\ type\ of\ perishable$
$food\ product\ f$

$DTF\{f\} = Destination\ \ that\ can\ receive\ perishable\ food\ f$

$FDF\{d2\} = Set\ of\ perishable\ food\ f\ that\ the\ final\ destination\ demands\ \ d2\ \in DF$

$FI\{i\} = Types\ of\ perishable\ food\ found\ in\ the\ area\ of\ production\ center\ i$

$FJ\{j\} = Types\ of\ perishable\ food\ that\ can\ be\ received\ in\ the\ colletion\ centers\ \ j$

$FK\{k\} = Set\ of\ perishable\ food\ that\ can\ be\ received\ by\ the\ \ wholesale\ center\ k$

$FOIJ\{o2\} = Set\ types\ of\ perishable\ food\ that\ can\ be\ sent\ by\ the\ origin\ \ o2 \in\ OIJ.$

$JF\{f\} = Set\ of\ colletion\ centers\ that\ can\ receive\ the\ type\ of\ fruit\ \ f.$

$IF\{f\} = Production\ center\ that\ produce\ the\ type\ of\ perishable\ food\ \ f.$

$KF\{f\} = Set\ of\ wholesale\ centers\ \ that\ can\ receive\ perishable\ food\ f$

$OIJ = Set\ of\ all\ possible\ origins\ up\ to\ link\ 2, index\ o2\ , OIJ = (I \cup J)$

$OIJF\{f\}$ = Set of origins up to echelon 2, which can send the type of food

$FDFD =\ Set\ of\ fruit\ that\ the\ final\ destination\ demands\ \ d2\ \in DF$

$FII =\ Set\ of\ fruit\ that\ are\ produced\ in\ Production\ center\ i$

A.3 Index

$f5\ in\ FDFD$

$f6\ in\ FII$

A.2 Parameters

$CAL_j = Minimum\ capacity\ of\ collection\ centers\ located\ in\ zone\ j$

$CAM_j = Maximum\ capacity\ of\ the\ colletion\ centers\ located\ in\ zone\ j$

$CTL_k = Minimum\ capacity\ of\ wholesale\ centers, k$

$CP_f =\ Cost\ of\ loss\ of\ perishable\ food\ type\ f$

$CTM_k = Maximum\ capacity\ of\ wholesale\ centers$

$$DNT_{d2} = \sum_{f5} DN_{f5d2} =\ Total\ customer\ demand\ \ d2 \in\ DF$$

$DN_{fd2} = Final\ destination\ demand\ d2 \in\ DF, of\ the\ type\ of\ perishable\ food\ f \in FDF\{d2\}$

$OFI_{fi}\ = Quantity\ of\ perishable\ food\ type\ f\ produced\ by\ the\ production\ center\ i$

$VEM_i = Minimum\ volume\ that\ must\ be\ sent\ from\ the\ production\ center\ i\ if\ it\ is\ included\ in\ the\ process$

$\alpha i_{fd2} = Demand\ porcentage\ that\ the\ final\ destination\ \ d2 \in\ DF\ has\ of\ the\ type\ of\ perishable\ food\ \ f$
$\in FDF\{d2\}\ \ for\ the\ production\ center$

$\alpha j_{fd2} = Demand\ porcentage\ that\ the\ final\ destination\ \ d2 \in\ DF\ has\ of\ the\ type\ of\ perishable\ food\ \ f \in FDF\{d2\}\ \ for\ the\ colletion\ centers$

$\alpha k_{fd2} = Demand\ porcentage\ that\ the\ final\ destination\ \ d2 \in\ DF\ has\ of\ the\ type\ of\ perishable\ food\ \ f \in FDF\{d2\}\ \ for\ wholesale\ centers$

$\gamma d2_{fd2} =$ Minimum demand percentage of fruit $f \in FDF\{d2\}$ which has to be received by client $d2 \in DF$ in case of being attended

A.3 Decision Variables

Excess of offer:

$SFI_{fo} = Amount\ of\ perishable\ food\ type\ f\ oversupply\ in\ echelon\ \boldsymbol{o}, \forall\ o \in\ I, J, K$

$SFID_{fd2} =$ Amount of the type of perishable food $f\ coming\ from\ the\ link\ \boldsymbol{e}\ overbid\ in\ the$

$final\ destination\ d2\ , \forall\ e \in\ I, J, K;\ \forall d2 \in\ DF; \forall\ f \in FDF\{d2\}$

A.4. Constraints

A.4.1 Flow balance in production centers

$$OFI_{f6i} * BPI_i\ = SFI_{f6i} + \sum_{d \in DTF\{f6\}} WN_{f6id} \qquad \forall\ i\ , \forall\ f6 \tag{5}$$

A.4.2 The flow of the production center that is not activated must be zero.

$$SFI_{f6i} \leq OFI_{f6i} * BPI_i \qquad \forall\ i\ , \forall\ f6 (6) \tag{6}$$

A.4.3 Control and opening with minimum flow in the production center

$$\sum_{f6} \sum_{d \in DTF\{f\}} WN_{f6id} \geq VEM_i * BPI_i\ \ i \tag{7}$$

A.4.4 Collection centers (CA):

$$\sum_{i \in IF\{f\}} WN_{fij} \left(1 - TN_{ij} - H_{ij}\right) = \sum_{d3 \in DIF\{f\}} WN_{fjd3} * \left(1 + \beta_{fj}\right) + SFJ_{fj} \quad \forall j, \forall\ f \in FJ\{j\} \tag{8}$$

A.4.5 Capacity and opening control

Collection centers (CA):

$$CAL_j * X_j \leq \sum_{i \in I} \sum_{f \in (FI\{i\} \cap FJ\{j\})} WN_{fij} \leq CAM_j * X_j \qquad \forall\ \ j \in FJ\{j\} \tag{9}$$

Wholesale centers

$$\sum_{o2\in OIJF\{f\}} WN_{fo2k} * (1 - TN_{o2k} - H_{o2k}) = \sum_{d2\in DFF\{f\}} WN_{fkd2} * \left(1 + \beta_{fk}\right) + SFK_{fk} \qquad (10)$$

$$\forall k, \forall f \in FK\{k\}$$

$$CTL_k * Y_k \le \sum_{o2\in OIJ} \sum_{f\in(FOIJ\{o2\}\cap FK\{k\})} WN_{fo2k} \le CTM_k * Y_k \qquad \forall k \qquad (11)$$

A.4.6 Minimum Demand for the first echelon per fruit (production centers)

$$\sum_{i\in IF\{f\}} WN_{fid2} * (1 - TN_{id2} - H_{id2}) = DN_{fd2} * \alpha i_{fd2} * \left(1 + \beta_{fd2}\right) + SFID_{fd2} \qquad (12)$$

$$\forall d2 \in DF, \forall f \in FDF\{d2\}$$

A.4.7 Maximum demand for the first echelon per fruit (production centers)

$$\sum_{j\in JF\{f\}} WN_{fjd2} * \left(1 - TN_{jd2} - H_{jd2}\right) = DN_{fd2} * \alpha j_{fd2} * \left(1 + \beta_{fd2}\right) + SFJD_{fd2} \qquad (13)$$

$$\forall d2 \in DF, \forall f \in FDF\{d2\}$$

A.4.8 Minimum demand for the second echelon (collection centers)

$$\sum_{k\in KF\{f\}} WN_{fkd2} * (1 - TN_{kd2} - H_{kd2}) = DN_{fd2} * \alpha k_{fd2} * \left(1 + \beta_{fd2}\right) + SFKD_{fd2} \qquad (14)$$

$$\forall d2 \in DF, \forall f \in FDF\{d2\}$$

A.4.9 Flow and opening relationships

$$WN_{fij} \le CAM_j * X_j \qquad \forall\ i,j,f \in (FI\{i\} \cap FJ\{j\}) \qquad (15)$$

$$WN_{fo2k} \le CTM_k * Y_k \qquad \forall\, o2 \in OIJ, k, \forall\ f \in (FOIJ\{o2\} \cap FK\{k\}) \qquad (16)$$

$$WN_{fid} \le OFI_{fi} * BPI_i \qquad \forall\, i, \forall\, d \in DT, \forall f \in (FI[i] \cap FDTJ[d]) \qquad (17)$$

A.4.10 Type of variables

The following set of constraints guarantees the decision variables domain and type.

$$X_j \in Binary\ \forall j \in J \qquad (18)$$

$$Y_k \in Binary\ \forall k \in K \qquad (19)$$

$$BPI_i \in Binary\ \forall i \in I \qquad (20)$$

$$WN_{od} => 0 , \qquad \forall\, o \,\in\, OT, \forall\, \, d \in DT \tag{21}$$

$$SFI_{f6i} => \, 0 , \forall\, i , \forall\, f6 \tag{22}$$

$$SFI_{fj} => \, 0 , \forall\, j , \forall\, f \in FJ\{j\} \tag{23}$$

$$SFI_{fk} => \, 0 , \forall\, k , \forall\, f \in FK\{k\} \tag{24}$$

$$SFID_{fd2} \;=> \, 0 \,\forall d2 \in \, DF, \forall\, f \in FDF\{d2\} \tag{25}$$

$$SFJD_{fd2} => 0 \,\forall d2 \in \, DF, \forall\, f \in FDF\{d2\} \tag{26}$$

$$SFKD_{fd2} => 0 \,\forall d2 \in \, DF, \forall\, f \in FDF\{d2\} \tag{27}$$