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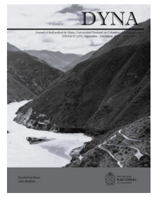

A mathematical model for optimizing the milk and cheese production chain in southern Nariño, Colombia

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Abstract
This study analyzes the milk production and processing chain in the southern region in Nariño, Colombia, through an optimization model aimed at improving the profitability of small-scale producers. Currently, about 44% of the region's milk is sent to collection centers and transported to large processing companies, resulting in frequent losses and reduced prices due to the product's perishability. The proposed model evaluates the creation of processing plants managed by local associations under a solidarity economy approach, for transforming a part of surplus milk and increasing producer income. The optimization model suggests establishing a plant in Guachucal, one of the region's top milk-producing municipalities, which could potentially double profits through the production of dairy derivatives such as cheese. Various scenarios were analyzed, supporting the feasibility of this strategy as a means to economically reactivate and strengthen the regional dairy sector.

Keywords: production chain; milk; supply chain optimization; Nariño.

Un modelo matemático para optimizar la cadena de producción de leche y queso en el sur de Nariño, Colombia

Resumen
Este estudio analiza la cadena de producción y transformación de leche en la región sur de Nariño, Colombia, mediante un modelo de optimización orientado a mejorar la rentabilidad de pequeños productores. Actualmente, cerca del 44% de la leche producida se envía a centros de acopio y luego a grandes transformadoras, generando pérdidas y bajos precios debido a la alta perecibilidad del producto. Se analiza la apertura de plantas de procesamiento gestionadas por asociaciones locales bajo un modelo de economía solidaria, con el fin de transformar parte del excedente de leche y mejorar los ingresos del productor. El modelo de optimización sugiere la instalación de una planta en Guachucal, uno de los municipios con mayor producción, lo que permitiría duplicar las utilidades al producir derivados como quesos. Además, se exploran diversos escenarios que respaldan la viabilidad de esta estrategia como mecanismo de reactivación económica y fortalecimiento del sector lechero regional.

Palabras clave: cadena productiva; leche; optimización de cadenas de abastecimiento; Nariño.

1 Introduction

The milk supply chain in Nariño is one of the most representative chains in the region due to the number of direct and indirect jobs that it generates. Nariño is the third-largest milk producer in Colombia, behind Antioquia and Cundinamarca, and accounts for 6-10 percent of the country's total milk production. According to the development plan 2024-2027 of Nariño, the milk supply chain contribution to the gross domestic product of the agricultural sector was about 27 percent in 2023. The milk supply chain included 39,862 direct producers and 159,448 indirect workers, yielding an estimated milk production of 1,009,747 liters per day based on statistics for the last semester of 2024 [1, 2].

The department of Nariño presents an important case study for the optimization of the milk and cheese supply

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chain in Colombia due to its significant role in national dairy production, its challenging geography, and the socioeconomic profile of its producers.

Specifically, most producers are small-scale farmers. Dairy production is dispersed across multiple small rural settlements (veredas) within municipalities, which complicates the collection and centralization of the product. Many producers form associations or cooperatives to sell their milk collectively, which gives them greater bargaining power. However, these organizations often face management and logistical challenges.

The department's topography, characterized by access roads in poor condition and frequent road blockades due to landslides or strikes, complicates timely milk collection, thereby increasing transportation costs and the risk of product loss. The milk is often collected in milk cans (cantinas) and transported in small vehicles, without the necessary cold chain, which can affect its quality. Many small producers lack access to refrigeration technology on their farms, forcing them to sell and transport the milk immediately after milking. Consequently, a portion of the milk must be transported warm, posing a risk to the quality of both the raw milk and its derived products.

All the above factors make the milk and cheese supply chain network design and optimization crucial to improving competitiveness and sustainability in Nariño. Any disruption or inefficiency in the supply chain not only affects the regional economy, but also directly translates into widespread economic vulnerability and a considerable social impact, which supports the design and application of optimization initiatives. The results of this paper suggest that an effective strategy for small producers would be to enhance their associative capacity to establish their own cheese production plants, thereby creating value-added products using a portion of the milk that would otherwise be sold to external companies.

A recent comprehensive review of the network design of agri-food supply chains, which includes milk and cheese, concludes that agri-food perishable-product supply chains remain understudied. The authors also highlight the need for not only considering location-allocation decisions, but also for including supplier selection in the models. In addition, the authors consider perishability as a key factor that can affect product life due to deterioration, supply chain disruptions, and quality problems of the initial raw products. Also, seasonality is considered as a key factor for supply chain design [3].

Guarnaschelli, Salomone and Méndez (2020) [4] apply a stochastic optimization model for integrating production and distribution in a dairy supply chain in Argentina. This chain consists of one manufacturing complex that produces 42 dairy products and has nine distribution centers. The model includes a single milk supplier in the formulation. The solution to the model requires a significant computational effort and therefore the authors divided the solution into two stage decisions. The results showed that considering randomness in the model can improve profitability, but at a significant computational effort.

An adequate structure of a supply chain allows for improved quality, good logistics performance, better response capacity, efficiency, and demand satisfaction [5]. A perishable supply chain has additional complexities, such as keeping the cold chain, controlling production time, optimizing transportation modes, and using the required storage of the product. In addition, biophysical and organoleptic characteristics of the product must be analyzed and considered to design the supply chain [6].

According to García, García and Cárdenas (2013) [7], to establish improvement processes throughout the supply chain, it is initially necessary to identify the variables that affect the system, and then to establish a set of logical mathematical and probabilistic relationships that integrate the behavior of the system, which is known as supply chain modeling. This is considered as a tool that supports decision making, since it provides an approximation of what would happen under certain conditions that affect the system, thus reducing risks and costs (which would be incurred) by not making the right decision.

Despite the importance of the dairy supply chain in Colombia, few studies to date have conducted a cross-cutting analysis of this sector, particularly in Nariño. Consequently, clear deficiencies and opportunities for improvement have not been systematically identified to inform interventions aimed at optimizing the chain's structure.

Tordecillas-Madera, Polo, Muñoz, and González-Rodríguez (2017) [8] present a binary optimization model to design a milk storage and refrigeration logistics system for a dairy cooperative in Ubaté, Colombia. This model includes cooling tank location, the allocation of producers to tanks (clusters), and system capacity calculation. The authors included supply chain robustness analysis in their publication by generating eight configurations and considering three supply scenarios (low, medium, or high). No production plants are included in the model.

Finally, an associativity scheme for the dairy chain in the department of Atlántico, Colombia, is presented in [9]. The authors analyzed variables such as Logistics, Quality, Production, and Associativity. The study showed that the associativity factor has a very low index compared to the other factors, and therefore it suggests the creation of new cooperatives to strengthen the sector's relationships. This study is fundamentally descriptive, and no optimization models are presented.

Modeling facilitates the management of a supply chain since, in addition to building a model of a complex system, its greatest advantage lies in the different applications that the model can have. In addition, it allows studying how the entire system is affected by small and large changes without having to implement them. This study performs an analysis of the fresh cheese production chain to identify key optimization points. Specifically, it presents the current structure and strategies that can improve the efficiency of the cheese production chain in associative enterprises in the department of Nariño. Modeling the most influential variables makes it possible to evaluate different scenarios, supporting well-informed decisions regarding the chain's improvement and competitiveness. This serves as a management tool for both private companies and territorial entities, which contributes to defining resource investment criteria to achieve better results for the chain.

Figure 1. Distribution of municipalities with the highest milk production in the Department of Nariño.
Source: DANE

The geographical distribution of the producing municipalities considered in this article is shown in Fig. 1. This region corresponds to the southern zone of the department, whose municipalities produce approximately 94 percent of the department's total milk. In the north of Nariño, while other municipalities do have livestock farming, their focus is on the production of meat or dual-purpose livestock, as the agroclimatic conditions are not suitable for milk production. For this reason, the southern zone in Nariño is a representative region of its total milk production.

In Nariño, approximately 56 percent of the milk produced in municipalities is converted into value-added milk products and 44 percent is sold to collection centers that transport the milk to large producers located in northern zones of the country (Table 1).

Table 1.
Milk availability for processing in existing plants or eventually new plants.

No	Municipality	Total (liters/day)	Milk for existing plants (liters/day)	Milk for collection centers (liters/day)
1	Guachucal	154,797	86,686	68,111
2	Cumbal	191,334	107,147	84,187
3	Pupiales	158,469	88,743	69,726
4	Pasto	105,699	59,191	46,508
5	Túquerres	96,630	54,113	42,517
6	Ipiales	88,359	49,481	38,878
7	Sapuyes	70,539	39,502	31,037
8	Tangua	59,031	33,057	25,974
9	Aldana	62,694	35,109	27,585
10	Cuaspud	53,277	29,835	23,442
11	Potosí	28,569	15,999	12,570
12	Iles	23,418	13,114	10,304
13	Gualmatán	20,493	11,476	9,017
14	Contadero	21,060	11,794	9,266
15	Guaitarilla	19,506	10,923	8,583
	Subtotal	1,153,875	646,170	507,705
	Percentage	100%	56%	44%

Source: Author's elaboration based on primary data collected through direct interviews with legal association representatives, municipal governments, and agricultural government officials in selected municipalities and collection centers. Specific source data cannot be released due to confidentiality agreements.

Based on the above considerations and the references reviewed, the specific contributions of this paper, not found in the literature, are the following:

- Modeling the southern Nariño dairy supply chain, including its main municipalities as milk suppliers
- Identifying the optimal location for one or more new plants to produce value-added products and performing sensitivity analyses for alternative locations
- Identifying the potential of producer associations to benefit small-scale milk producers
- Considering the transportation of both cold and warm milk throughout the supply chain

Section 2 presents the optimization model. In Section 3, the model results are discussed, and some key sensitivity analyses are conducted. Finally, Section 4 presents the conclusions of the article.

2 Methodology

2.1 Milk supply chain characterization and echelon identification

Collection centers: Collection centers are facilities where milk is collected from several producers and cooled in stainless steel tanks with modular systems that are easy to install. The cooling process conducted at collection centers allows the milk to be transported in a cooling network over long distances minimizing product deteriorating.

Milk from the collection centers is purchased by companies in the north of the country, such as Colanta and Alpina, which have a presence in Nariño's milk-producing municipalities. These companies have large collection centers where milk is consolidated and shipped in 10,000- or 20,000-liter tanks to their processing plants.

Existing processing plants: The processing plants, as well as the collection centers, are in areas of high milk production to reduce freight and transportation time. Once the milk arrives at the plant, there is no further transportation; the milk is only stored for processing during the day.

The existing plants produce a variety of products, the most processed being fresh farmer's cheese and curd cheese, and to a lesser extent other derivative such as heavy cream cheese, mozzarella, and fermented beverages such as yogurt.

Since the plants are small with processing ranges mostly between 5,000 and 15,000 liters of milk/day, they do not have solid commercial logistics. Their marketing channel depends on intermediaries who end up setting sales prices according to supply/demand variations. These marketers mostly buy products at the processing plants and transport products to the main cities in the north of the country.

Considering the above situation, it has become evident that, for the producer/processor organizations, the process of marketing to intermediaries is not competitive, since there is no fair relationship between the parties and the commercial alliances are not agreed under contracts that allow stabilizing sales prices. Therefore, with a growing demand for fresh cheese consumption, one alternative that has been proposed for the department is to implement new processing plants on an associative basis, so that they manage their own transportation and marketing of their product to final consumers, trying to shorten intermediation in the supply chain.

Figure 2. Fresh cheese supply chain in Nariño
Source: Source: Author's elaboration based on primary data collected through direct interviews with legal association representatives, municipal governments, and agricultural government officials in selected municipalities and collection centers. Specific source data cannot be released due to confidentiality agreements.

The milk that is considered available for the implementation of new processing plants is that which is sent to collection centers destined for plants in the north of the country. On the other hand, the milk that goes to existing processing plants, for the purposes of mathematical modeling, is maintained as a demand to be satisfied in terms of milk consumption, since these companies have a market segment of internal demand that they already serve in the department and the milk they receive is of a lower physicochemical and microbiological quality than that received at the collection centers. Accordingly, the profit made by existing plants from their finished product sales is not considered here as a supply chain profit; only the milk sales from municipalities are included in the supply chain profit.

There is a growing demand for fresh cheese in the north of the country, which needs to be met by cheese produced in Nariño. There are several small plants (existing plants) in the department that are not efficient enough to meet the demand at competitive prices, and most of them are managed by private, non-associative companies. Therefore, this study proposes the implementation of new cheese production plants. However, the factors associated with this process, such as location, volume to be processed, raw material supply routes, and distribution routes, among others, are unknown. An illustrative diagram of the supply chain for milk and its derivatives in the Department of Nariño is shown in Fig. 2. We next formulate the mathematical optimization model for the shown supply chain.

2.2 Sets and indexes

CA: Set of existing collection centers, indexed by n
CD: Set of distribution centers (DCs) where the external demand is located, indexed by q
NP: Set of new plants or potential locations to open a plant, indexed by k
P: Set of finished products, indexed by p
PE: Set of existing plants, indexed by j
PROV: Set of municipalities that supply milk, indexed by i

2.3 Parameters

AMORT = Fixed daily amortization of civil construction and equipment when investing in a new plant (it is assumed that this amortization does not depend on the location where a new plant is to be opened) (COP/day)
CENF = Cost of milk cooling (COP/liter)
CLF = Transportation cost of cold milk (COP/liter per hour)
CLT = Transportation cost of warm milk (COP/liter per hour)
$CPAST_k$ = Transportation cost from the new plant k to the municipality of Pasto where consolidation takes place to ship finished products to external customers´ DCs in the northern part of the country (COP/kg)
CPL = Production cost of milk in farms (COP/liter)
$CTCD_q$ = Average transportation cost from the municipality of Pasto to external DC q (COP/kg)
$CTRANSFN_p$ = Conversion cost of product p in new plants (COP/kg)
$DEME_{pq}$ = External demand of product p at the external DC q (kg/day)
$DEMLE_j$ = Milk demand at existing plant j (liters/day)
$PROD_i$ = Production capacity of milk at each municipality i (liters/day)
PV_p = Selling price of product p (COP/kg)
PVCA = Buying Price of milk at collection centers, assumed to be the same for all of them (COP/liter)
PVPE = Buying Price of milk at existing plants, assumed to be the same for all of them (COP/liter)
R_p = Finished product yield when converting milk into a finished product p (liters of milk/kg of finished product)
$RUTAE_{ij}$ = Binary parameter equal to 1 if milk supplier i is located at a place where the transportation time to the existing plant j is more than 180 min, so that the milk must be cold to be transported; 0, otherwise.
$RUTAN_{ik}$ = Binary parameter equal to 1 if milk supplier i is located at a place where the transportation time to the new plant k is more than 180 min, so that the milk must be cold to be transported; 0, otherwise.
TE_{ij} = Estimated travel time from municipality supplier i to existing plant j (min).
TN_{ik} = Estimated travel time from municipality supplier i to a new plant k (min).
VMIN = Minimum milk volume to be processed so that a new plant would be profitable (liters/day)

2.4 Decision and auxiliary variables

$FPNDE_{pkq}$ = Flow of product p from new plant k to external distribution center q (kg/day)
$varl_{pk}$ = Amount of product p to be produced in new plant k (kg/day)
W_i = Amount of milk to be sent from municipality supplier i to its associated collection center (it is assumed that each municipality that produces milk has only one associated collection center located in the same municipality) (liters/day)
X_k = Binary variable equal to 1 if a new plant is opened at the potential site k; 0 otherwise.
Y_{ik} = Amount of milk that is transported from municipality supplier i to new plant k (liters/day).
Z_{ij} = Amount of milk that is transported from municipality supplier i to existing plant j (liters/day).
The above variables are illustrated in Fig. 3.

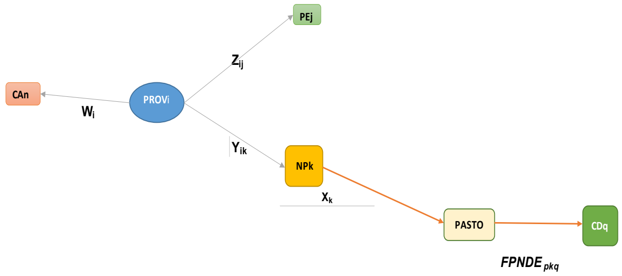

Figure 3. Illustration of the mathematical model decision variables
Source: Own elaboration

2.5 Constraints

1. Municipality supplier *i* will supply all the daily amount of milk to new plants, existing plants, or collection centers:

$$\sum_k Y_{ik} + \sum_j Z_{ij} + W_i = PROD_i \quad (\forall\, i) \qquad \left(\frac{liters}{day}\right) \tag{1}$$

2. A municipal supplier *i* will transport milk to a new plant only if it is open:

$$Y_{ik} \leq PROD_i X_k \quad (\forall\, i, k) \qquad \left(\frac{liters}{day}\right) \tag{2}$$

3. External demand satisfaction constraint. The flow of finished products from new plants must satisfy the external demand (if this is profitable) by product *p* and by external distribution center *q*:

$$\sum_k FPNDE_{pkq} \leq DEME_{pq} \quad \forall\, p, q \qquad \left(\frac{kg}{day}\right) \tag{3}$$

4. Minimum milk volume to be processed for profitable conversion at new plants:

$$\sum_i Y_{ik} \geq VMIN\, X_k \quad \forall\, k \qquad \left(\frac{liters}{day}\right) \tag{4}$$

5. Milk demand satisfaction at existing plants. The milk coming from all municipalities to each existing plant must satisfy its demand:

$$\sum_i Zij = DEMLE_j \quad \forall\, j \qquad \left(\frac{liters}{day}\right) \tag{5}$$

6. Balance of milk at each new plant:

$$\sum_i Y_{ik} = \sum_{p,q} FPNDE_{pkq} R_P \quad \forall\, k \qquad \left(\frac{liters}{day}\right) \tag{6}$$

7. Auxiliary variable. Production of each finished product at each new plant *k*:

$$varl_{pk} = \sum_q FPNDE_{pkq} \quad \forall\, p, k \qquad \left(\frac{kg}{day}\right) \tag{7}$$

8. Flow control of finished products from new plants when either they are closed or open (by product, external distribution center and new plant):

$$FPNDE_{pkq} \leq DEME_{pq} X_k \quad \forall\, p, k, q \qquad \left(\frac{kg}{day}\right) \tag{8}$$

9. Flow control of finished products from new plants when either they are closed or open (by product and new plant):

$$varl_{pk} \leq M\, X_k \quad \forall\, p, k \qquad \left(\frac{kg}{day}\right) \tag{9}$$

10. Variable definition:

$$FPNDE_{pkq}, varl_{pk}, W_i, Y_{ik}, Z_{ij} \geq 0;\ X_k\ binary \quad \forall\, i, j, k, p, q \tag{10}$$

2.6 Objective function

Three sources of profit have been identified according to the route taken by daily milk production estimated by the mathematical model:

a) Profit from milk sales to collection centers (UCA)
b) Profit from milk sales to existing plants (UPE)
c) Profit from the conversion of milk and sale of finished products from new plants (UPN)

$$Max\ Z = Overall\ profit\ of\ the\ milk\ and\ cheese\ supply\ chain \quad \left(\frac{COP}{day}\right) \tag{11}$$

Total profit of milk sales at collection centers (*UCA*):

$$UCA = Income\ from\ sale\ of\ milk\ at\ collection\ centers - Cost\ of\ milk\ production\ on\ farm$$

$$UCA = \sum_i W_i (PVCA - CPL) \tag{12}$$

It is important to note that transportation costs are not considered in this part of the objective function because farms located in each municipality can only send milk to the associated collection center located at the same municipality, which is usually close to the farms to avoid the deterioration of milk properties.

Total profit of milk sales to existing plants (*UPE*):

$$UPE = Income\ from\ sale\ of\ milk\ to\ existing\ plants - Cost\ of\ milk\ production\ on\ farm - Transportation\ cost\ (i,j)$$

$$UPE = \sum_{i,j} Z_{ij}(PVPE - CPL) - \sum_{i,j} Z_{ij}\, CLT \left(\frac{TE_{ij}}{60}\right)(1 - RUTAE_{ij}) - \left(\sum_{i,j} Z_{ij}\, CLF \left(\frac{TE_{ij}}{60}\right) RUTAE_{ij} + \sum_{i,j} Z_{ij}\, CENF\ RUTAE_{ij}\right) \tag{13}$$

Total profit from milk conversion and sales of finished products from new plants (*UPN*):

$$UPN = Income\ from\ finished\ product\ sales\ sent\ by\ new\ plants - Milk\ transportation\ costs\ from\ municipalities\ (i,k) - Production\ costs\ at\ new\ plants - Transportation\ costs\ from\ new\ plants\ to\ Pasto\ and\ from\ here\ to\ northern\ cities\ (Popayán, Cali, Pereira) - Amortized\ cost\ from\ the\ investment\ in\ new\ plants.$$

$$UPN = \sum_{p,k} varl_{pk} PV_p - \sum_{i,k} Y_{ik} CLT \left(\frac{TN_{ik}}{60}\right)(1 - RUTAN_{ik}) - \left(\sum_{i,k} Y_{ik} CLF \left(\frac{TN_{ik}}{60}\right) RUTAN_{ik} + \sum_{i,k} Y_{ik} CENF\ RUTAN_{ik}\right) - \sum_{i,k} CPL\ Y_{ik} - \sum_{p,k} varl_{pk} CTRANSFN_p - \sum_{p,k,q} FPNDE_{pkq} CTCD_q - \sum_{p,k,q} FPNDE_{pkq} CPAST_k - \sum_{k} AMORT\ X_k \quad (14)$$

Note that the income from milk sales from municipalities to new plants is not considered here because this item is an income for municipalities, but it is also a cost for new plants and thus it vanishes for the supply chain.

$$\boldsymbol{Max\ Z} = UCA + UPE + UPN \quad (15)$$

3 Results and discussion

3.1 Optimal solution to the original model

The above model was run in the *neos server*, using the *gurobi solver*. The first significant result is that the optimal solution opens a single plant located in the municipality of Guachucal, with a maximum daily profit of 373,800,805 COP/day. The optimal configuration of the supply chain is shown in Fig. 4. The milk suppliers that would supply the new plant with their associated volume are shown in Table 2 and the milk suppliers that would supply the existing plants are shown in Table 3.

Table 2.
Milk suppliers of the new plant to be opened in Guachucal.

Municipality	Milk volume (liters/day)
Aldana	27,525
Cumbal	14,118
Guachucal	154,797
Total Flow of milk	**196,440**

Source: Own elaboration

Table 3.
Milk suppliers of existing plants.

Origin municipality	Destination municipality	Milk volume (liters/day)
Túquerres	Túquerres	54,113
	Guachucal	16,617
Contadero	Contadero	11,794
Cuaspud	Cuaspud	29,835
Guaitarilla	Guaitarilla	10,923
Aldana	Aldana	35,109
Gualmatán	Gualmatán	11,476
Iles	Iles	13,114
Guachucal	Guachucal	70,069
Ipiales	Ipiales	49,481
Pasto	Pasto	59,191
Cumbal	Guachucal	70,069
	Cumbal	107,147
Potosí	Potosí	15,999
Pupiales	Pupiales	88,743
Sapuyes	Sapuyes	39,502
Tangua	Tangua	33,057
Total		**716,239**

Source: Own elaboration

The flows of milk to the collection centers are shown in Table 4. This result shows that the municipalities that feed the new plant stop supplying milk to the collection centers, because, for the entire supply chain, it is more profitable to sell the milk to the new plant. This confirms the fact that it can be more profitable to add value to the milk and sell the finished products than to sell it entirely to external production plants. However, there is still a significant flow of milk to the collection centers and therefore the external plants could continue to be supplied.

Another result to highlight is that the expected external demand in the northern cities of the department of Nariño is fully satisfied by the mathematical model, demonstrating the profitability of the current estimated sales prices. Regarding the profit components in the objective function, it is interesting to observe the result in Table 5, which shows that profit can double if the chain processes its own milk instead of selling it to collection centers.

Table 4.
Milk supplies to collection centers located in each municipality.

Municipality	Volume to be sent to collection centers (liters/day)
Túquerres	25,900
Contadero	9,266
Cuaspud	23,442
Guaitarilla	8,583
Aldana	0
Gualmatán	9,017
Iles	10,304
Guachucal	0
Ipiales	38,878
Pasto	46,508
Cumbal	0
Potosí	12,570
Pupiales	69,726
Sapuyes	31,037
Tangua	25,974
Total	**311,205**

Source: Own elaboration

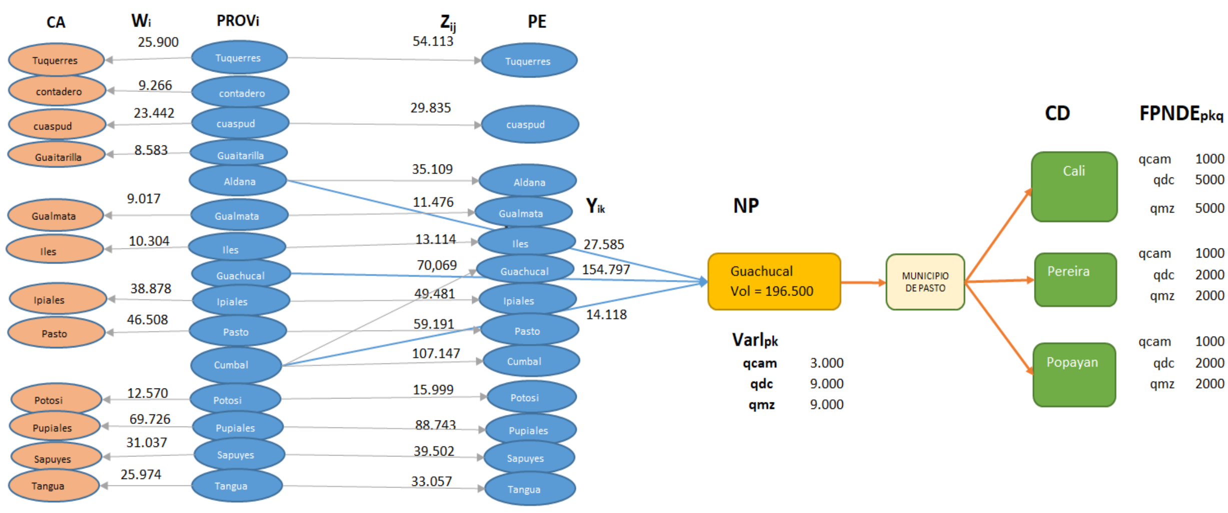

Figure 4. Optimal solution to the original mathematical model (qcam = farmer´s cheese, qdc = double cream cheese, qmz = mozzarella cheese).
Source: Own elaboration.

Table 5.
Relative percentage of the objective function components.

Component in the objective function	Optimal value (COP/day)	Relative percentage
Profit of milk sales at collection centers (*UCA*)	93,361,500	25%
Profit of milk sales to existing plants (*UPE*)	99,164,900	27%
Profit from production and sales of finished products at new plants (*UPN*)	181,274,405	48%

Source: Own elaboration

3.1 *Sensitivity analyses*

3.2.1. Scenarios about changes in new processing plant location

To analyze the effect of opening the plant in another municipality, with the use of configuration constraints, the change in the profit generated shown in Table 6 was evaluated. It can also be concluded that, although the municipality of Pasto is a good milk producer in Nariño, locating a plant in this municipality is not ideal considering that it is in another sub-region where there is low milk production and therefore it is necessary to collect milk from distant municipalities. If the plant is opened in this municipality, profits would decrease by 3.18 percent.

Table 6.
Maximum profit when a single plant is open in each municipality.

Municipality to open the plant	Maximum profit (COP/day)
Guachucal	373,800,805
Cumbal	373,686,029
Ipiales	373,144,012
Pupiales	373,006,334
Aldana	373,000,628
Cuaspud	372,245,850
Túquerres	372,137,288
Sapuyes	371,618,242
Potosí	371,501,884
Contadero	371,305,093
Gualmatán	371,174,225
Tangua	369,844,279
Guaitarilla	369,656,158
Iles	368,140,691
Pasto	361,911,674

Source: Own elaboration

3.2.2. Scenarios about demand variation

Table 7 shows the results for fluctuating demand, by decreasing or increasing it with respect to the value originally considered. A reasonable decrease in external demand does not modify the original optimal location in the municipality of Guachucal. Likewise, when demand increases up to 20 percent, the optimal location does not change. When the demand increases by 25 percent, two new plants are open, including Guachucal. However, if we force the model to open a single plant in Guachucal, then the optimal profit decreases only by 0.016 percent. When the demand increases by 30 percent, the model opens two plants different from Guachucal. Nevertheless, if in this case we force the model to open a single plant in Guachucal, the optimal profit decreases only by 0.043 percent. We consider both profit decreases negligible. Therefore, the option to open a plant in the municipality of Guachucal is satisfactory for the demand changes shown in Table 7.

Table 7.
Effects of demand variation on the optimal location and the objective function.

% external demand variation	New plant optimal location	Total supply chain profit (COP/day)	Volume of milk processed (liters/day)
−20	Cumbal	349,603,430	157,200
−15	Guachucal	355,636,542	167,025
−10	Guachucal	361,725,183	176,850
−5	Guachucal	367,774,368	186,675
0	Guachucal	373,800,805	196,500
+5	Guachucal	379,827,243	206,325
+10	Guachucal	385,853,680	216,150
+15	Guachucal	391,880,118	225,975
+20	Guachucal	397,906,555	235,800
+25[a]	Guachucal Pupiales	403,996,000	245,625
+25[b]	Guachucal	403,932,993	245,625
+30[a]	Cumbal Pupiales	410,087,199	255,450
+30[c]	Guachucal	409,911,390	255,450

Source: Own elaboration
[a] In these cases, two new plants are opened in the optimal solution.
[b] This is the optimal solution when the model is forced to open a single plant.
[c] This is the optimal solution when a single new plant is forced to be opened in Guachucal.

4 Conclusions

In this work, it has been possible to identify the economic importance of the dairy supply chain for the Department of Nariño, Colombia. The structure of the network has facilitated the analysis of its current behavior and the possible points of improvement for the benefit of small producers in the Department of Nariño.

In relation to the results generated from the location of the new processing plant in the municipality of Guachucal, it can be concluded that the results are consistent in the sense that it is a highly milk-producing region surrounded by other producing municipalities at short distances, which optimizes transportation costs in the different scenarios proposed.

The generation of agro-industrial transformation processes for milk generates positive effects in terms of higher profit margins for small producers. Considering the physicochemical characteristics of milk, it is better for the chain to transport cheese with added value than to transport milk as a raw material. Further research in this area may include the more precise consideration of the distribution channels of finished products, the inclusion of warehousing and holding inventory costs, and the analysis of the cold supply chain of finished products, among others.

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