Milk Collection Optimization in the Dairy Cluster of Atlántico, Colombia

Ronald Andrés Corcho Martinez

Tesis de maestría presentada para optar al título de Magíster en Ingeniería

Directores

Juan G. Villegas Ramírez, Doctor (PhD) en Ingeniería y Optimización de sistemas industrial

Pablo A. Maya Duque, Doctor (PhD) en Investigación de Operaciones

Universidad de Antioquia
Facultad de Ingeniería

Maestría en Ingeniería

Medellín, Antioquia, Colombia

2022

Maestría en Ingeniería

Grupo de Investigación Analítica e Investigación para la Toma de Decisiones (ALIADO).

Centro de Investigación Ambientales y de Ingeniería (CIA).

Acknowledgements

First, thanks God for giving me health, love, support and putting on my path the people I met in the development of this study.

This study is dedicated to a special person in my life and now my Angel in heaven (***Reinaldo Corcho Wilches***, ***Daddy***). I felt your support and happiness in every step, paragraph, and word of the process. For you with all my heart and love. I know you are proud of me. Love you forever dad, see you in the future.

I would like to thank the following people/entities:

- For the love, support, encouragement without whose help this work would never have been possible: Esilda Martinez Valenciano, Reinaldo Corcho Martinez, and Alejandra Berdugo Alonso.

- For their support, without their valuable suggestions and discussions this work would never have been possible: Juan Guillermo Villegas Ramirez and Pablo Andres Maya Duque. Two excellent people, professors, tutors, and friends. You are two cracks.

- For the strategies, understanding and support during the covid 19 pandemic to the Antioquia University.

- This research was benefited from a grant from Atlántico Gubernation and the Ministry of Science, Technology, and Innovation: Minciencias.

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Chapter I

Introduction

1.1 Dairy Industry

The world's consumption of milk has been growing since the '80s. The Food and Agriculture Organization of United Nations (FAO) predicts a growth rate of milk production of 2.5% per year for 2020-2030 [1]. Furthermore, FAO estimates that per capita consumption in developing countries will increase 50% in this period [2]. The dairy industry is one of the main components of the agribusiness economic sector [3]. Agribusiness can be seen as a supply chain, where the interactions of different actors allow relations to develop, transform and distribute supplies and final products in this economic sector [3]. Currently, logistics is becoming a cornerstone of competitiveness and economic performance in a globalized economy context. Consequently, countries are focused on creating strategies to generate an efficient logistics framework to address the entire spectrum of the supply chain [4]. In Atlántico (a northern state of Colombia) in their 2020-2023 planning, the agricultural sector was determined as a strategic area for economic, social, and environmental development, based on efficient use of resources, the modernization of agriculture and generation of business culture to improve the income levels of the municipalities and promote the sustainability of businesses such as livestock and agriculture [5],[6]. Considering the free trade agreements signed by the country's government in recent years, it is imperative to increase productivity and reduce operating costs in the dairy sector to guarantee the access of its products to the markets [7]. Particularly, the Colombian Department of Atlántico has been working on the dairy cluster under the "AtlantiLAC" initiative since 2014. The cluster generates a daily production of 250,000 liters of raw milk [8]. In order to increase productivity and reduce costs, several problems and challenges have been identified in the supply chain of the dairy sector. One of them is the inefficiency of the milk collection logistics due to the lack of efficient operating models and the atomization of producers (long traveling distances) [9],[10].

The milk collection problem is a well-known problem in rural areas around the world [11]. Also is known or addressed as the dairy transportation problem [6]. This problem consists in collecting the raw milk in the farms, which generally are scattered in a wide geographic region and away from processing plants [12]. Milk collection should be performed as soon as possible, according to FAO within four hours of milking [13]. Besides, the markets and manufacturing plants are located near or in urban areas, while milk is produced by small producers and most of whom have limited or no storage capacity [13].

The milk collection process can be studied from the perspective of logistics planning [14]. Decisions are hierarchically divided into strategic, tactical, and operational [15]. At the strategic-tactical level, the milk collection problem can be addressed as a districting problem, whose decisions belong to the design of the network [16]. In this case the aim is to group the farms to minimize the distances to be covered in collecting due to the dispersion of the network [17],[18]. Districting has a function to simplify a large problem into smaller subproblems or promote groups with similar characteristics [19], so districting prior to routing generation is considered a strategy that improves efficiency in product collection [20],[21]. This has motivated the current work to solve the milk collection at strategic-tactical level in Atlántico, through a districting design strategy to minimize the distances to be covered in a subsequent routing while consolidating the farms into districts and optimizing the composition of the fleet.

The cost of collection has a direct impact on profitability of the milk supply [6]. Also, the transportation cost is a significant component proportion in the total cost in any organization that requires collect or move commodities or raw material [22]. In the Colombian dairy sector context, the milk collection costs represent 33% of the logistics costs [23], being above the average in the dairy sector worldwide [13].

This problem reduces the competitiveness of the sector and motivates the development of the current study to tackle the milk collection decision in the dairy cluster of Atlántico, through a districting design strategy. This strategy aims at minimizing the distances to be covered in a subsequent routing (collection) while consolidating the farms into districts and optimizing the composition of the fleet. An improvement in terms of costs due to shorter travel distances is expected.

This thesis is divided into four (4) chapters. Chapter I gives a brief overview of the problem and motivation of current work. The next two chapters (II and III) are developed in a self-contained article format. The second chapter presents a literature review focusing on studies that addressed the milk collection problem on how the operations research or prescriptive analytics methods have been used in the milk collection context. The conclusions of this chapter validate the relevance of this research. The third Chapter presents a case study where the milk collection planning of the Atlántico Department is addressed as a districting problem. Particularly, this chapter presents a location-allocation multi-objective optimization model to tackle the districting problem in milk collection. Finally concluding remarks, and the discussion for future work in the area are given in chapter IV.

Chapter II

Prescriptive analytics in Milk collection: an operations research review

2.1 Introduction

The milk collection problem can be considered as a variant of the vehicle routing problem (VRP) [11], but it is more complex due the special characteristics and attributes of the dairy industry context [24]. Hence, elements from the VRP taxonomy are used to define the following four dimensions to be analyzed: problem setting, decisions, characteristics/constraints, and methodological approaches. In recent years there has been considerable interest in studying this problem. This interest could be motivated by the fact that milk is one of the most produced and valuable agricultural products. As of 2018 world production accounts 864 million liters and global sales of dairy products to US$ 501 billion [25]. Furthermore, the dairy sector contribute to the fulfillment of some of the sustainable development objectives such as: ending poverty by being a community livelihood (especially in developing countries), decent work and economic growth through employment generation, and zero hunger and food security based on the importance of dairy products as a nutrient source in public health [26].

It is well known that milk collection is a problem in rural areas around the world [11]. A remarkable feature of this problem is that farms are scattered in a wide geographic region and away from processing plants, where the raw milk is collected [12]. Considering the perishable nature of raw milk, the logistical challenge increases because the product must be collected and transported as soon as possible to the collection centers or manufacturing plants [27]. One of the objectives in the raw milk collection process is to maintain the temperature of milk around four to seven degrees Celsius until it is delivered to the processing plant so that its quality is not affected [13]. The raw milk transport conditions vary depending on the size of producers (farm). Usually, small producers store the raw milk in milk churns which are transported by themselves or through intermediaries on trucks, while big producers store raw milk in milk cooling tanks for preservation. After consolidation, the milk is transported on tanker trucks, which keep the right temperature for the product [13]. Nevertheless, the producers should decide what is the most appropriate way to transport raw milk so that transport cost is as low as possible [28].

According to [29], in the dairy supply chain context, the milk collection is considered at second level process within the decision making hierarchy depicted in Figure 1.

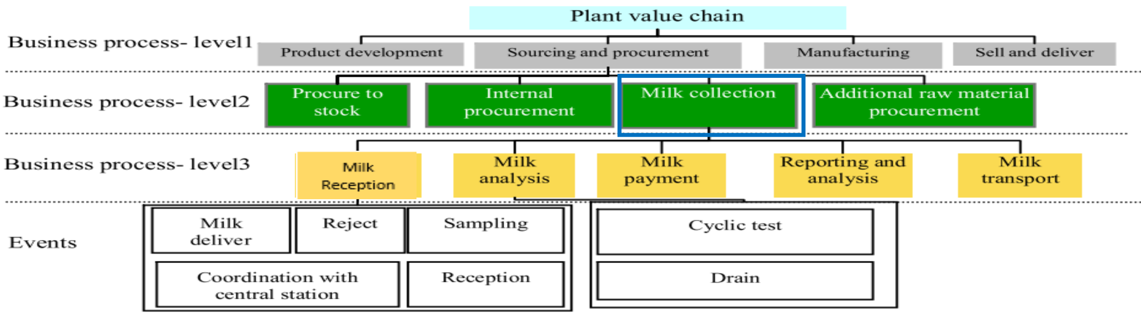


Figure 1. Decision making hierarchy in the Dairy supply chain (Malihi & Aghdasi, 2014).

When studied from the perspective of logistics planning [14], the decisions involved in the milk collection process are hierarchically divided into strategic, tactical, and operational [15]. At the strategic level, we found decisions related to the planning and design of the logistics network, like the well-studied districting, facility location and transportation network design problems [20]. At the tactical level, we found decisions such as transport mode selection and fleet composition. Finally, the operational level considers decisions such as vehicle routing and vehicle allocation [30],[31].

This chapter i.) identifies the decisions considered in milk collection planning, ii.) identifies the problem characteristics / constraints that are considered, iii.) describes the solution approaches (methods and methodological approaches) that have been used to tackle the problem.

The remainder of this chapter is organized as follows. Section 2.2 presents the methodology used in the literature review; Section 2.3 presents the discussions and analysis of the literature; Section 2.4 ends the chapter with conclusions and some future research directions that were identified in the review process.

2.2 Literature Review

2.2.1 Search methodology

The papers considered in this review were gathered using a mixed review methodology, that is, mixing systematic review and backward review based on the references of previously identified papers. First, for the systematic literature review we chose the SCOPUS database and designed the search equation which is shown in Figure 2. We only include papers written in English and published in academic journals. PhD or master thesis, as well as conference proceedings were excluded from the search.

The search retrieved 57 papers. The preliminary review, based on scanning the title, abstract, and keywords indicated that 24 out of the 57 papers were pertinent for the review.

Then, those 24 documents were used to perform a backward literature review based on their references, identifying another 23 relevant papers. Hence, this review is based on 47 documents.

TITLE-ABS-KEY ("Milk Collection“ OR "Dairy Collection“ OR "Dairy Transportation“ OR "Milk Transportation") AND ("Optimization" OR "MILP" OR "Model Programming" OR "Simulation" OR "Metaheuristic" OR "Heuristic")

Figure 2. Search algorithm Milk Collection.

2.2.2 Descriptive analysis of the search results

The milk collection problem was addressed (with this name) for the first time in 1983. Since then, the problem is increasingly becoming an interesting field to researchers. Figure 3 shows the number of published papers on this problem by year. Almost half of the papers were published after 2010, showing a slight increment in the last five years.

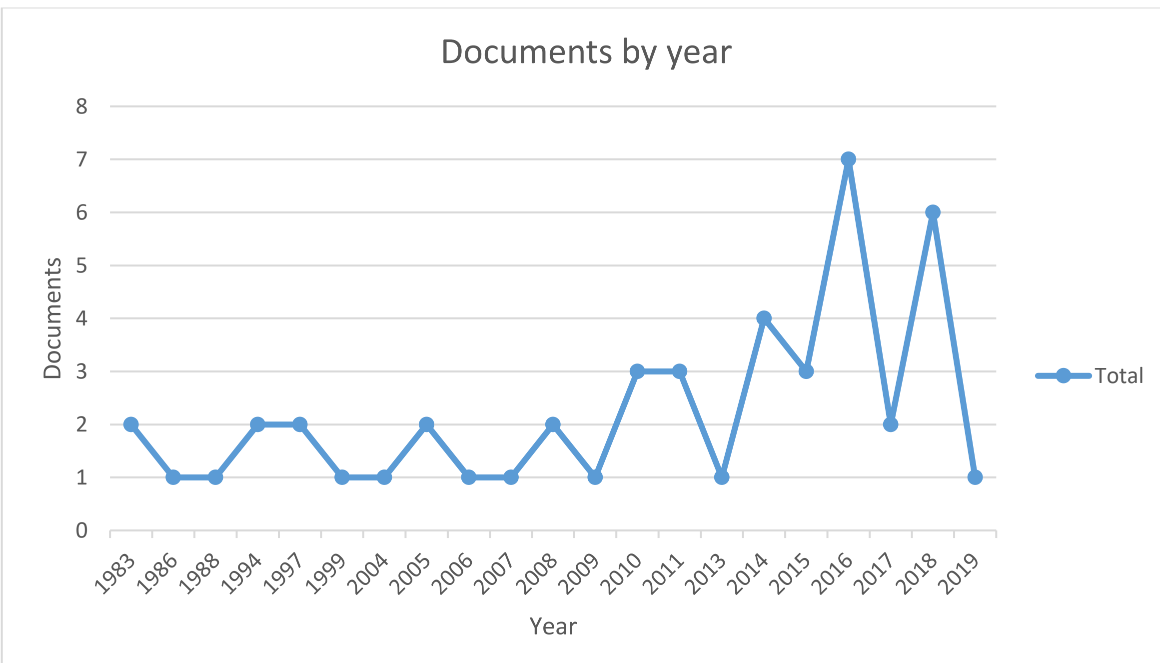


Figure 3. Works per year milk collection problem.

2.2.3 Analysis and classification Process

In order to provide a framework, the milk collection problem can be classified using four dimensions, namely: problem setting, decisions, characteristics/constraints, and methodological approaches, which are shown in Figure 4.

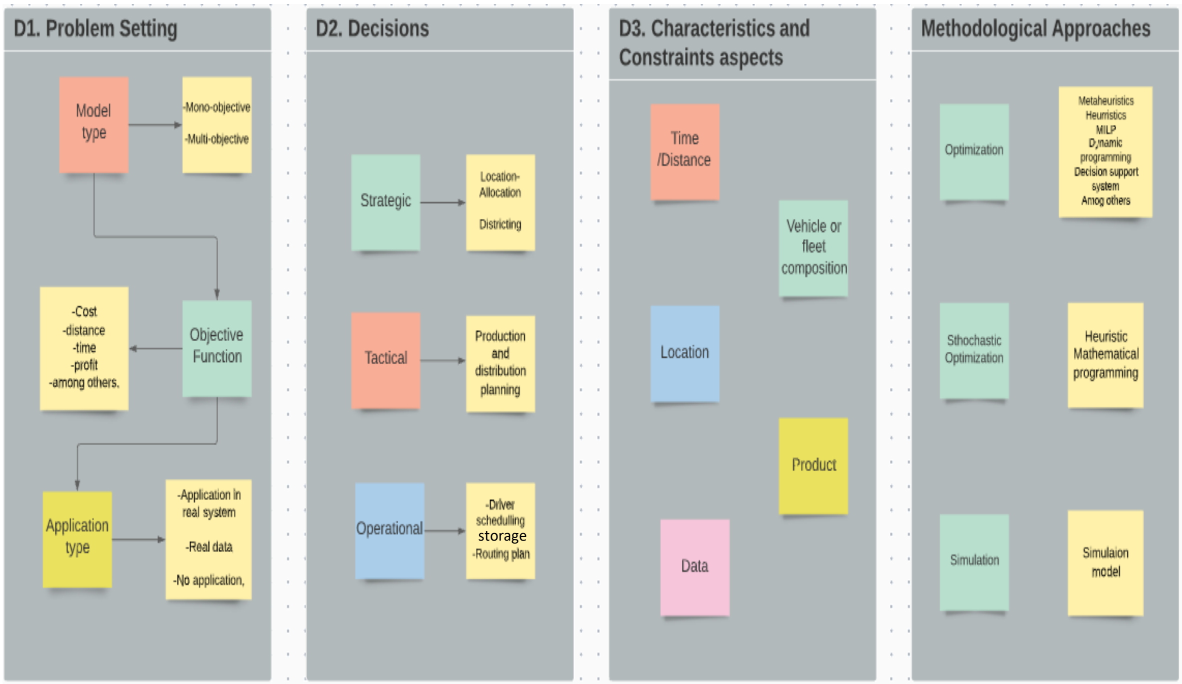


Figure 4. Milk collection problem classification framework.

First, problem setting is identified according to the model type, features considered in function objective and used data (application type). Second, decisions are classified by the level of decision. Third, characteristics and constraints are defined and differentiated by five aspects according to time/distance, fleet, location, product, and data. Finally, the methodological approach is identified according to the prescriptive analytics approach used to tackle the problem. In addition, problem contexts are defined by main characteristics/constraints addressed.

A brief overview of the four dimensions used to analyze the papers follows:

Problem setting

The papers are classified based on their aims (objective function), model type, problem context and application type, as shown in Table 1. The aims are based on objective function in each paper. The model type indicates if the model has a single objective or multiple objectives. The application type determines whether the used data is randomly generated without real application (randomly generated), based on a real problem or a case study (real-data based), or their solution is implemented in real system (implementation in real system).

Objective Function	Model Type	Application type
Cost	Mono-Objective	Real data based
Distance	Multi-objective	No application - Randomly Generated
Time		Implementation in real system
Profit		
Fleet		
Demand		
Environment		
Revenue		
Number of facilities		

Table 1. Problem setting features.

Decisions

Decisions represent those factors under the control of the decision-maker. For the analysis we considered three levels of decisions. Strategical, tactical, and operational. Strategic decisions are classified either in districting or location-allocation collection centers, production and distribution planning at a tactical level, and scheduling drivers or vehicle routing at the operational level. See Table 1.

Strategic	Tactical	Operational
Districting or Clustering	Production and distribution planning	Driver scheduling
Location - allocation collection Point or depot		Routing Plan
		Inventory control and Storage

Table 2. Decisions components.

Location–allocation determines the location of collection points serving customers and sometimes, the related routing plan simultaneously [32]. Districting is addressed as a two phase approach “cluster first - route-second” as an alternative to the traditional approach to solve the vehicle routing problem, in this case the aim is to group the farms in order to minimize the distances to be covered in the collection stage [17]. Production and distribution planning was first introduced by Lahyani et al. [33], the aim is to determine the quantity to produce for each item, and their distribution plans. The driver scheduling decisions are about performing vehicles and drivers' schedules simultaneously [32]. Finally, the routing plan decisions are to determine the set of vehicle routes and sequence to visit the customers [32]. Inventory control and storage decisions are related to the quantities of milk that will be stored in intermediate nodes of the supply chain and the selection of the equipment needed to store the raw milk [13].

Characteristics and constraints

There is a vast collection of constraints and problem characteristics that have been considered. The chosen documents are analyzed based on the following five aspects: time/distance, vehicles or fleet, location, product, and data that are shown in Table 3. The aspects are adapted from the taxonomy introduced by Lahyani et al in [32] to analyze the literature devoted to Rich Vehicle Routing Problems (RVRPs) (see Appendix A). This taxonomy is designed according to central concepts in routing that are often present in operation research and analytics applications in the milk collection problem.

As a contribution, we add other subclasses to extend the taxonomy to the milk collection problem, those subclasses are i.) the problem context to describe how the milk collection is formulated or addressed as a variant of another (well known) problem (see subclass 1.2), ii.) time or distances constraints which are specified to operation, customer, road, or methodological approach (see subclass 2.2). iii.) product constraints that are associated with the presence of different product qualities, the option of blending the milk in the transportation process (see subclass 2.7). iv.) the location characteristics related to the plant requirements and farm requirements. Moreover, some subclasses such as loading policies, driver regulation, Backhauls, Dial-a-ride of [32] were removed because do not apply in the milk collection context (see subclass 2.8). Next, further details on these aspects are given.

Time/Distance Aspect	Vehicles or Fleet Aspect	Location Aspect	Product Aspect	Data Aspect
Time or distance contraints	Homogeneous vehicles	Colection points	Quality	Dynamic data
Time windows	Heterogenous vehicles	Industry or plant requeriments	Flow and mass conservation constraints	Deterministic data
Uncertainty and vulnerability	Refrigerated vehicles	Attention requirement of each farm	Blending	Stochastic data
Service, waiting and/or travel time	Capacity	Single depot	Not blending	
Dead distance	Environment	Multi depot		
Single period	Compartmentalized	Splitting allowed		
Multi-period	Not compartmentalized	Splitting not allowed		
Incompatibility	Multi-trip	Accessibility		
	Single trip	Preassignments		
	Fixed			
	Unlimited			

Table 3. Aspects of characteristics and constraints.

Time/distance: This feature classifies the characteristics or constraints related to periods considered in the collection plan over a given time horizon. The uncertainty and variability considering stochastic features of the problem such as travel time uncertainty or demand variability. Incompatibilities both physical and temporal. Constraints related to the service, waiting time, traveling time, or constraints to define the service at every customer must start and finish within a given time window.

Vehicles or fleet: This feature classifies characteristics and constraints such as fleet composition either homogeneous or heterogeneous and fixed or unlimited, customer environmental awareness, and characteristics closely related to the milk collection operation like refrigerated vehicles, vehicles with compartments or not compartmentalized, and multiple uses of vehicles during the planning period.

Location: This feature classifies the constraints and characteristics related to locations such as farms, collection points, depots, or plants present in a logistic network. Plant requirements (how much of each product is required by each plant), collection periodicity, multiple vehicles serving a farm (load splitting). The number of depots present in the logistic network. Sometimes some customers cannot be served by a given type of vehicle, which implies accessibility constraints. Likewise, occasionally, some vehicles, customers or farms are pre-assigned to a depot, route, or plant.

Product: In this feature the characteristics related to the product are described. Different qualities of the product, blending and compartmented transport. Sometimes, it is necessary to establish the flow and mass conservation constraints due to transshipments, presence of multiple depots, collection points, or demand splitting.

Data: This feature considers three classes of data depending on the uncertainty and the variability of the data. The most common is deterministic data, which assumes the problem parameters are known with certainty, whereas stochastic values assume the knowledge of probability distributions to model the uncertainty present in data. Dynamic data assumes that the adjustment of the initial plan is possible according to new information that is known dynamically while it has been executed.

Methods and methodological approaches

This dimension outlines the methodological approach to address the problem and what method is used to find solutions. See Table 4.

Methodological Approach	Method
Optimization	Metaheuristic
	Heuristic
	Mixed Integer Linear Programming
	Mixed Integer Programming
	Dinamyc programming
	Scheduling program
	Decision support system
Sthochastic Optimization	Heuristic
Simulation	Simulation model

Table 4. Methodological approach features.

Methodological approach determines the technique used to tackle the problem, namely, optimization, simulation, or stochastic optimization.

Problem Context

Five general problems were identified as the main used for the modelling of milk collection such as vehicle routing problem, supply chain management problems, vehicle allocation problem, scheduling problem and traveling salesman problem. Other problems were identified as subproblems or specific variants of these main problems. These variants or specialized extensions arise from the inclusion of additional characteristics to the problem. See Figure 5 and Appendix B.

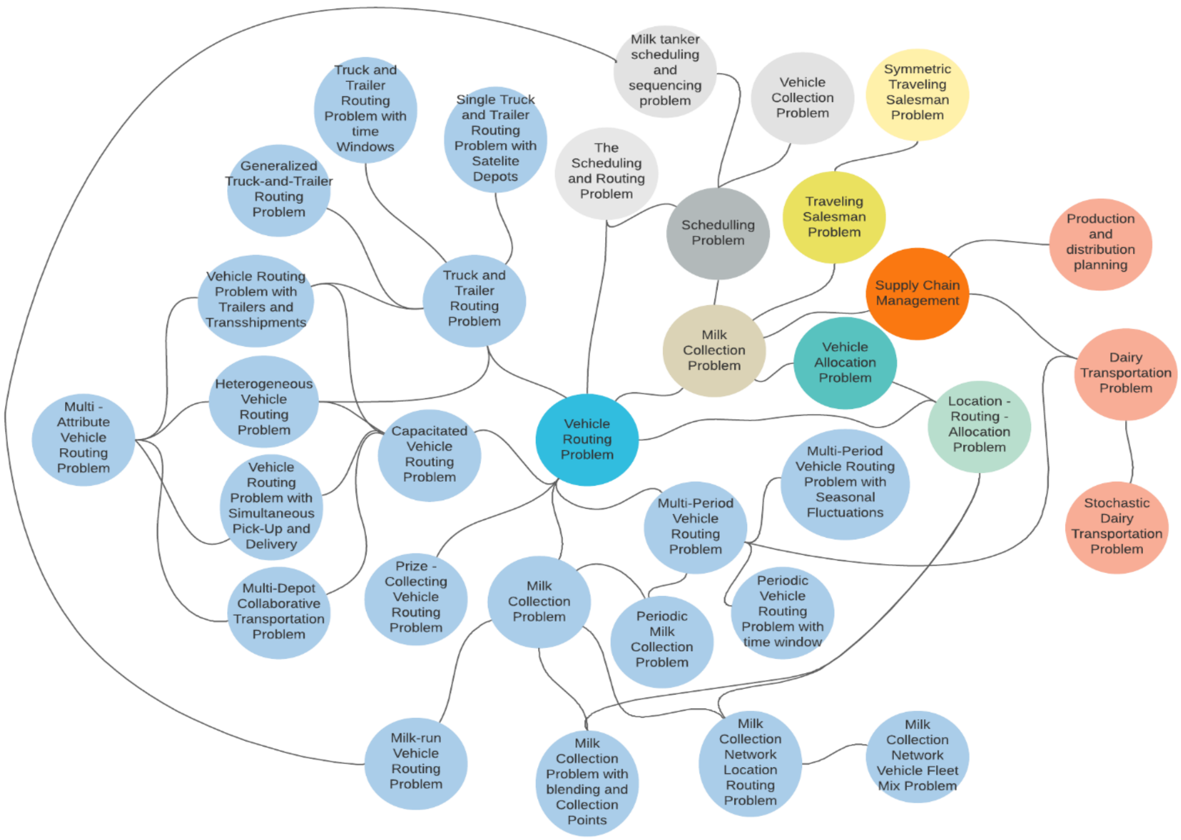


Figure 5. Problem contexts milk collection problem.

2.3 Discussion and Analysis

2.3.1 Problem setting

The cost has been widely addressed or used in objective functions, as it was considered in 22 out of 47 papers (47% of the works). Usually the objective function minimizes collection [34],[35] or transportation cost [36],[27]. However, in some cases, the costs also consider other features such as milk demand [37], cleaning costs of the raw milk tanks [24], facility operation costs [38], and fixed fleet costs [39]. Second, 16 out of 47 documents use the distance as objective function (34% of the works). In this case, the aim is to minimize the total distance of the collection routes [40]-[41]. Time has been included in 7 out of 47 documents in the objective function (15% of the works). It usually aims at minimizing the total time spent in the collection process [42], collection lateness at each farm [43] or makespan minimization [44]. Additionally, in a few cases the aim is to minimize the size of the fleet [11],[45], maximize the operation profit [12],[29], or minimize the environmental impact [34],[46].

There is a considerable amount of literature where the authors formulate the problem in a single objective model, this happens in 38 out of 47 documents (81% of the works). While the remaining works (9 of 47 documents) formulated it as a multi-objective model. To address the milk collection problem, the authors usually based their solution approach on other problems already studied in the vehicle routing literature. Many studies have been published using the truck and trailer routing problem as the underlying model (13%, 6 out of 47 documents) and vehicle routing problem (11%, 5 out of 47 documents).

Regarding the application type, 47% are applications with data based on real milk collection operations or case studies, other 40% used randomly generated data without real application, and only 13% describe an implementation in a real system. For further details see Appendix C.

2.3.2 Decisions

The different type of decisions considered are not mutually exclusive between them, so some of them can be approached simultaneously. There is a considerable amount of literature that addresses the milk collection problem in one or more levels of decisions at the same time as shown in Figure 6.

Figure 6. Venn diagram for decisions.

Hence, a useful feature to observe is the different combinations of decision levels that have been addressed. The milk collection problem has been tackled as a variant of the vehicle routing problem (VRP) [11], thus operational decision level has been widely addressed. In fact, most researchers have addressed the problem with operational decisions. A total of

98% of works (46 out of 47 documents), either faced the routing plan (45 out of 46 documents) and/or the driver scheduling (9 out of 46 documents).

Moreover, there is a considerable amount of literature on the milk collection problem with only operational decisions, in 38% of the works (18 out of 47 documents). 17 out of 18 works considered routing plan decisions [47],[48],[49], while 4 of those works include driver scheduling decisions [11],[44]. In only one case the authors focused on driver scheduling decisions [50]. Also, various papers have integrated operational decisions with strategic or tactical decisions, in 21% (10 out of 47 documents) and 26% (12 out of 47 documents) of the papers, respectively. In the integration with strategic decisions 6 out of 10 works address location – allocation collection point and routing plan decisions jointly [35],[38],[39],[51]. In 3 out of 10 documents the authors tackle districting and routing plan decisions simultaneously [52]-[53], and only one approached at the same time location-allocation collection point, districting, and routing plan decisions [27]. In the integrated tactical decisions all twelve works analyze the routing plan and production planning decisions [24],[36],[37], and only 4 of those documents also approach driver schedulling decisions [24],[42]. Only one work considers tactical level decisions uniquely [29].

Furthermore, it is interesting to highlight that 13% of the works (6 out of 46 documents) approach decisions at strategic, tactical, and operational levels simultaneously. In 4 of those documents considered districting, production and distribution planning, and routing plan decisions [12],[41],[54]. The remaining two works addressed only location–allocation collection point allocation decisions [18],[55]. For further details see appendix D.

2.3.3 Characteristics and constraints

Modeling the milk collection problem generates the need to face some characteristics and constraints based on the decisions to address. As reported previously the characteristics/constraints are sorted into five features (time/distance, vehicles or fleet, location, product, and data). First, we analyzed the distribution of these features according to the main characteristics as shown in Figure 7.

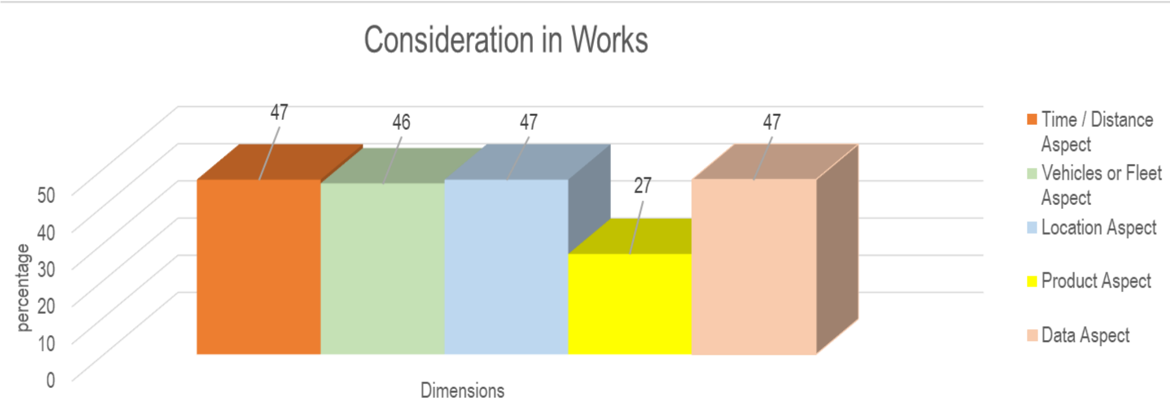


Figure 7. Frequency of characteristic aspects in works.

The time/distance, location and data features have been widely investigated, at least one constraint or characteristic belonging to them is considered in all works. Then, the vehicle or fleet feature is almost as studied as the previous one (46 out of 47 documents), only one work does not consider any constraint or characteristic belonging to this dimension. Clearly, the product is the least considered in the works so far. Since this feature was neglected by most of the authors in the 80's and 90’s.

Time/distance: There is a vast amount of literature considering period characteristics, either single period 72% of the works (34 out of 47 documents) or multi-period in 28% of the works (13 out of 47 documents). These characteristics are related to periods to be considered in the collection plan over a given time horizon, in literature multi-period is related to the periodic vehicle routing or production – or distribution planning problems [6],[36],[43],[54],[56],[57]. Second, many studies consider incompatibility constraints, 27 out of 47 documents (57% of the works). Incompatibilities could be both temporal and physical either as precedence constraints in synchronization between tours [24],[37],[46],[51] or inclusion and exclusion restrictions that may occur as a milk-type incompatibility [11],[58]. Then, other features used frequently are distance/time constraints in 45% of the works (21 of 47 documents), time constraints have been found used to limit the maximum amount of time for a trip [34],[57], the initial time when a vehicle can reach a point *j* from the point *i* [47], implement time-updated constraints to facilitate routing synchronization [51]. In the last decade, there has been a growing interest in using distance constraints to meet compact clusters and minimize traveling distance, when districting decisions have been addressed [12],[27]. Furthermore, in the literature there are many examples (16 out of 47 documents) about service time, waiting time, and traveling time to estimate route duration [6], the transportation time in distribution routes [57]. Moreover, this aspect also includes time windows, considered in 26% of works (12 out of 47 documents) to impose that the service at each customer start and/or end within a given time interval [42],[49],[57]. Finally, few studies have been published on uncertainty–variability characteristics or constraints, that been addressed in only three documents, such as travel time uncertainty [42], supply variability [41], uncertainty present in the production process [59], and deadhead distance (distance traveled without load on the vehicle) used in only a single document [34].

Vehicles or fleet: The characteristics and constraints related to the vehicles or fleet are important in modeling, due to operational implications in this problem context. The capacity constraints have been found to be a key feature in the vehicle routing problem, present in 96% of works (45 out of 47 documents), such that the total demand on each route, collection center, depot, or plant does not exceed its capacity [32]. In this aspect, some features are mutually exclusive such as fleet composition (homogeneous or heterogeneous), vehicle compartment type (compartment or not), and trip frequency (single or multi-trip). In fleet composition, heterogeneous fleet has been identified as being more considered (57% of works, 27 out of 47 documents) than homogeneous fleet (38% of works, 18 out of 47 documents) [37],[46]. Related to size of the fleet, fixed fleet is considered in 91% of works (43 out of 47 documents) while unlimited fleet is present in only 4% of works (2 of 47 documents). In this real-world context, there are generally limited resources (vehicles) and these have heterogeneous sizes and capacities [12],[38]. Many studies have been published on other physical and logistic characteristics such as compartmentalized vehicles in 15% of works (7 out of 47 documents) or not compartmentalized in 63% of works (29 out of 47 documents). Related to multiple use of vehicles, the most considered is a single trip for each vehicle in 66% of works (31 out of 47 documents), where each vehicle can perform one trip during the planning period [42],[48]. Whereas multiple trips were considered in 32% of works (15 out of 47 documents), the same vehicle performs several trips during the planning period [43],[57]. Recently there has been considerable interest in refrigerated vehicles as a feature considered by authors in 23% of works (11 out of 47 documents), specialized trucks to transport the milk [34],[43]. In addition, few studies have been published on the environment characteristic, present in only one document to minimize the environmental impact (CO2 emissions) [34].

Location: It is common in the milk collection problem that each farm requires to be served at least once, 46 out of 47 documents. There is only one selective/prize collection routing variant [37]. Next, forbidden load splitting were considered in 89% of works (42 out of 47 documents). However, the possibility of multiple visits to the same farm (i.e., load splitting) has been considered in 6% of works (3 out of 47 documents) [24],[45]. In this case, the results highlight the comparison of the effect of both practices on milk collection [12]. Then, the other characteristic considered is the number of depots, multi-depots in 43% of the works (20 out of 47 documents) [36],[41],[46], and single depot in 26% of works (12 out of 47 documents) [39],[42],[51]. Similarly, there is a considerable amount of literature including collection points, with 32% of works (15 out of 47 documents) including this feature [6],[18],[40]. Otherwise, many studies have been published on constraints related to plant requirements (how much of each product is required by each plant), in 40% of works (19 out of 47 documents), Then, various studies have proposed accessibility constraints, in 34% of works (16 out of 27 documents), these constraints are related to the possibility of access a farm with a given vehicle type, generally in the truck and trailer routing problem context [35], [52],[60]. Finally, not much is known about pre-assigned feature, present in only one work [6], due to contracts that assign transporters to specific plants.

Product: In the product feature, there are many examples of flow and mass conservation constraints, in 45% of works (21 out of 47 documents) [18],[38], this characteristic is necessary for context like transshipment [51]. Recently, there has been considerable interest in including different types of milk qualities (product classification), in 23% of works (11 out of 47 documents) [12],[18]. In some cases blending different qualities of milks is not allowed, considered in 13% of documents (6 out of 47 documents), either to prevent different qualities not be mixed [58], or to maintain traceability of milk for each collection point [24]. Otherwise, few studies have been published on blending different quality of milk (2 out of 47 documents). In [12],[18] blending milk is allowed to reduce transportation costs, but simultaneously, the revenue also decreases.

Data: Deterministic information is the most common type of data used in the literature, in 94% of works (44 of 47 documents), assuming problem parameters are known with certainty. Not much is known about dynamic data, used in 5% of works (2 out of 44 documents), related to plants that adjust their seasonal demands according to the supply [36],[56]. Whereas the stochastic data were used in only 6% of works (3 of 47 documents), this feature is related to uncertainty and vulnerability characteristics. e.g., travel time uncertainty [42], include the variation of the demand [41], and production, and demand as stochastic variables [59]. More details on characteristics and constraints are given in the appendix E.

2.3.4 Methodological approach and solution methods

Three methodological approaches have been identified in the reviewed works, namely, optimization, simulation-optimization, and stochastic optimization, in 89%, 9% and 2% of the papers, respectively. In the optimization approach, there is a considerable amount of literature that used approximated methods to tackle the problem, such as metaheuristics in 38% (16 out of 47) and heuristics in 26% (11 out of 47) of works. In metaheuristics, various approaches have used infeasible solutions as a part of the search space to solve this issue (9 out of 16 documents). Moreover, metaheuristics are used in hybrid methods. In the literature, there are several examples of tabu search [6],[27],[45],[55], GRASP [37],[43],[52], local search, or their variants and variable neighborhood search [11],[27]. Also traditional metaheuristics like simulated annealing have been used [49],[61] or new methods based on a population of solutions such as the differential evolution algorithm [24].

Intensification of greedy randomized adaptive search procedure (GRASP) characterized some hybrid solution strategies, and variable neighborhood search (VNS) or variable neighborhood descent (VND) enhanced the local search embedded to add diversification [43],[52],[62]. Other hybrid methods are based on local search (intensification) and tabu memory component (diversification) embedded to guide the solution search [27],[45]. Regarding the solution approaches based on heuristics, 3 of 11 documents consider multi-stage algorithms [48],[53],[63], either to solve subproblems such as clustering and routing, or to improve solutions. Heuristics based on column generation [39], or branch and cut approaches [51] have also been used.

Many studies have been published on used exact methods such as mixed integer linear program (MILP), in 24% of works (10 out of 42 documents). Some preliminary work was conducted in the early 1990s with the branch and bound approach [44],[64]. In [54] the authors investigated the special ordered sets. Several studies, for example [56],[65] have been conducted on branch and price approach with dynamic programming or tabu search heuristics. And a recent review of the literature on this topic found multi-stage heuristic procedure [12],[18]. Furthermore, other methods used in optimization approach are decision support system based on algorithms such as clustering and traveling salesman problem algorithms [66], critical path and greedy algorithms [50], or scheduling programs (software) [67].

In the literature, there are few examples on Simulation & optimization approaches used in this context, in 4 of 47 documents. In all of them the simulation model has embedded metaheuristics such as large neighborhood search [40], ant colony system [34], genetic algorithm [29], or heuristics such as nearest insertion algorithm - local search [59]. Not much is known on stochastic optimization approach, used in only one work that implemented a set covering heuristic [42].

It is interesting to analyze how the methodological approaches and methods have been used according to the decisions considered, see Figure 8. Metaheuristics are more frequently used indistinctly the level or levels of decisions addressed. This is due mainly to their capability for handling large-scale instances. Nevertheless, when the three levels of decision or tactical and operational decisions are considered jointly, authors have also used MILP frequently combined with decomposition approaches. When the problem includes strategic and operational decisions jointly or only operational decisions, authors have also used heuristics. For the case in which the only decision level is tactical, simulation was the preferred alternative. Please refer to Appendix F for further details.

Figure 8. Usage of methods according to decision and interactions.

2.3.5 Milk Collection with districting decisions

In the literature, few studies have addressed districting decisions in milk collection, 18% of works (9 out of 47 documents), All of them consider routing decisions at the same time. In 55% of those works (5 out of 9 documents) production and distribution planning decisions (in this context supply) [12],[41] are so tackled. While in 2 out of 9 documents the researchers add the location-allocation of collection center decisions [18],[27], no driver-scheduling decisions are present in any work. See Figure 9 and Table 5.

The formulation is mono objective in all works. Cost, distance, or profit have been identified as being the feature most considered in the objective function. In addition, include the following constraints or characteristics, vehicle capacity constraints, vehicles without compartments, homogeneous or heterogeneous fleet, plant requirements, no-load division, milk quality types, among others.

Optimization is the methodological approach used in all works. Many studies have used approximative methods (metaheuristics or heuristics) to tackle the problem, in 6 out of 9 documents. Such as greedy randomized adaptive search procedure (GRASP) [52], taboo search (TS) [6], local search (LS) [27], adaptive large neighborhood search (ALNS) [41]. Components such as memory, random search, and adaptive search characterized those methods. The remaining works (3 of 9 documents) used mathematical programming and commercial optimizers with branch and cut algorithms as the main methodology to tackle and solve the problem [18],[54]. Further details see appendix G and H.

Decisiones	Documentos
Districting	9
Location - allocation collection Point or depot	2
Production and distribution planning	5
Driver scheduling	0
Routing Plan	9

Figure 9. Venn diagram decisions in milk collection context. Table 5. Decisions levels milk collection.

In [12] the authors investigated the problem using a "cluster first-route second" approach to maximize profit considering three milk types of quality, a minimum volume requirement for each type, and income increase based on this quality in milk collection in southern Chile..

Then, in [18] the authors address the milk collection problem bearing in mind milk types qualities and add location-allocation collection center decisions within the logistics network, first locate the collection centers and second assign the farms to them so small producers can store the milk in these points through an ad-hoc coverage model. A k-means method was used to address the "cluster first - route second" approach and generate clusters. To minimize the sum of the distances to the center, this algorithm locates k virtual points and assigns the farms to the closest virtual point according to a distance criterion. Besides, the k value is selected heuristically considering if the number of subproblems grows the global solution worsens, but those are easier to solve [12]. In another case [6], Lahrichi et al. address the vehicle routing problem with time windows considering districting decisions. It assigns depots to carriers then farms to deposits, thus each carrier covers an area with multiple depots.

2.4 Conclusions of the Chapter

This review has led us to conclude that the milk collection problem is an interesting problem to address, considering the strategic, tactical, or operational decisions. The findings of this review support the idea that few studies have been published on strategic decisions (Districting and/or location-allocation of collection centers). Recently, districting decisions have been incorporated due to the positive effect that they generate on the subsequent routing. In general, the results suggest a mono-objective model is used to approach the milk collection problem (81% of 47 documents), being cost, time, and distance the most common.

The findings of this study indicate that four of the five features of characteristics and constraints have been widely investigated. Nevertheless, constraints related to the product have been gaining much attention due to the interest in including features such as different qualities of the product, allow blending and compartmented transport. The evidence from this review suggests the idea that authors frequently address constraints related to periods to be considered in the collection plan (single or multi-period) and distance/time constraints in time/distance feature. Also, supports the idea that characteristics and constraints related to vehicle feature are important in modeling, such as capacity constraints, fleet composition (heterogeneous or homogeneous), trip frequency, and physical and logistic characteristics (vehicles compartmentalized or not). Regarding location, attention requirement is an inherent characteristic. Also, features such as the number of depots in the logistics network and not splitting load have been widely investigated. Otherwise, there are few examples of work considering collection points or industry plant requirements.

Thanks to the capability of metaheuristics for handling large-scale and complex problems. This is the preferred solution approach indistinctly the level or levels decision address in the milk collection problem. Nevertheless, when the strategic and tactical level decision is considered, authors have also used mathematical programming formulations and commercial optimizers with branch and cut algorithms.

The review made in this chapter remarks on the importance of milk collection and how districting decisions have been used in this problem. Districting decision applications in the milk collection context, do not frequently address the location-allocation of collection center decisions jointly. Mono-objective model is used to devise the problem keeping in mind cost, distance, or utility within the aim model. Besides, consider characteristics such as vehicle and collection centers capacity constraints, vehicles without compartments, homogeneous or heterogeneous fleet, plant requirements, no-load division, and quality types of milk.

Chapter III

Districting in milk collection - a case study

3.1 Introduction

Milk is one of the most produced and valuable agricultural products [25]. In 2018, milk world production was 864 million liters and global sales of dairy products reached US$ 501 billion [25]. The Food and Agriculture Organization of the United Nations (FAO) predicts a milk production growth rate of 2.5% per year for 2020–2030 [1]. Also, FAO estimates that per capita consumption in developing countries (such as Colombia) will increase by 50% in this period [2]. Additionally, the dairy sector directly or indirectly contributes to the fulfillment of sustainable development objectives [26].

According to [29], the dairy supply chain involves different processes ranging from the production to distribution and consumption. One of the first processes in the chain is milk collection, which is considered a second-level process within the hierarchy of processes. In developing countries, this process has become critical in the supply chain because the markets and manufacturing plants are located in urban areas or their surroundings, while the production is located in small farms far from cities and with limited or no storage capacity [13]. According to FAO, the collection should be performed as soon as possible (four hours from the milking) [13]. In the Colombian dairy sector, the milk collection process is inefficient due to the lack of proper operating models and the atomization of producers [9],[10]. The cost of milk collection represents 33% of logistics costs, a value above the world average (30%) hindering this sector competitiveness [13],[23].

In the literature, the milk collection process is denoted as the milk collection problem, which is a well-known problem in rural areas around the world [11]. This problem consists in collecting the raw milk produced in the farms, which generally are scattered in a wide geographic region and away from processing plants [12]. Some preliminary work was conducted in the early 1980s, in [67] the problem was addressed (with this name) for the first time. However, since 2010 there is a growing interest in this problem.

The milk collection problem is considered a special variant of the vehicle routing problem [11]. Considering logistics planning, the milk collection involves strategic, tactical, and operational decisions [14]. The latter has been considered in most of the related literature. However, in recent years strategic and tactical decisions such as districting [41], the location and allocation of collection centers [18], or the production and/or supply planning [37] have been considered when tackling the problem. When addressed as a districting problem at the strategic level, the decisions involved are associated with the design of the network [16]. In this context, districting is usually tackled as part of a two-phase approach (i.e., first find allocation to the collection centers then determine which customers should be served for each center), in contrast to the traditional approach based on the vehicle routing problem [17]. One of the main aims of districting is to group the farms to minimize the distances to be covered in the collection due to the dispersion of the network [18]. The districting decisions have proved to be an effective strategy to consider before the collection to improve its efficiency [19],[20]. The optimization approach is the main solution methodology used to tackle the problem, specifically mathematical programming, and metaheuristics.

This chapter proposes a new approach to incorporate the districting problem into milk collection to tackle the identified inefficiency. We present a districting model with decisions regarding the location of collection centers, the allocation of producers to them and the fleet composition of each collection center.

The remainder of this chapter is organized as follows. Section 3.2 gives a brief overview of the districting problem and districting decisions in milk collection. Section 3.3 introduces the mathematical formulation of the problem. Section 3.4 presents the solution and implementation strategy, a brief overview of multi-objective optimization and methodology used to solve the proposed model. Section 3.5 presents a case study based on the dairy cluster of Atlántico (a northern state of Colombia) which is used to validate the model. Section 3.6 describes the computational experiments, evaluation metrics, and the analysis of results. While the action guidelines report based on analysis of experiments results are reported in Section 3.7. Finally, some conclusions and future research directions are drawn in section 3.8.

3.2 Districting Problem - DP

The districting or territory design problem is a subfield of discrete optimization related to partition decisions [68]. The districting problem was first studied in the 60s when dealing with the problem of partitioning areas in a political context in order to prevent the manipulation in elections (gerrymandering) [69]. Depending on the application context, it is also known as territory design, zone design, redistricting, p-regions, or regionalization [70]. Typically, the districting problem is defined as a set of basic units that has to be divided into districts or territories that satisfy a series of planning requirements [68]. The planning requirements are defined according to the specific application and economic or demographic considerations that motivated them [71]. Although each problem is different and has requirements that makes it unique, there are common elements to most of the districting problems. The interested reader is referred to [68] for a recent and comprehensive overview of the DP and its solution methods and applications.

Two mathematical formulation approaches have been used in the literature to model DPs, namely, set partitioning and location-allocation [72]. Preliminary work in this field focused primarily on the location-allocation approach to maximize the compactness of districts as another way to obtain contiguity [73]. This approach is also referred to in some cases as facility-location, where the district centers are not set by default, but they must be selected from a set of potential locations [72]. Otherwise, the districting problem can be addressed under a set partitioning approach [17]. The set partitioning approach does not require a set of potential centers of the districts to be specified. Instead, the set of all feasible districts is assumed to be available, and decisions select a subset of them [72]. Location-allocation has been the most used approach to address the districting problem.

The most common criteria in DPs are compactness, contiguity and balance with respect to one or several measures such as workload, sales, clients, farms, population [17]. Time–distance and capacity constraints have also received considerable attention. In [74], the authors used the distance constraints to limit the maximum distance that production areas (basic units) can have from the maintenance service facilities (centers) allocated to them.

Regarding the objective functions, there is a great amount of papers on single objective functions. A common aim is to maximize the workload balance (based on some activity measure) or to maximize compactness. In [75], the objective is to maximize compactness which is tackled by minimizing the maximum distance between a center and any of its basic units. Although less frequent than mono-objective models, some multi-objective formulations have been proposed. This type of model has limitations to find solutions in non-convex regions and requires the use of Pareto criteria or weighting objectives techniques [76]. Nevertheless, it is possible to analyze trade-off between objectives [77].

Based on the reviewed literature, the main solution approach to tackle the districting models is optimization [17], even using exact methods (mathematical programming) or approximate methods (metaheuristics and heuristics). Other methodologies have been used with less frequently, such as discrete events simulation [78], or robust optimization (stochastic programming) [79]. In [74], the authors formulated a multi-objective integer programming model and used the ε-constraints method to identify a set of Pareto optimal solutions. Similarly, [80] describes an integer programming model (MILP) with location binary variables and relaxed allocation variables to gradually allocate basic units to districts. While, [81] presents a MILP with a procedure to generate an upper bound, which makes the model more efficient by using it in the preprocessing to set and eliminate binary variables. The current technology and MIP solvers can solve instances with up to 10,000 basic units in reasonable computing time [17],[68].

Regarding approximate methods, metaheuristics have been designed in a single or hybrid approach and include components such as random search (GRASP, simulated annealing, neighborhood search), memory (tabu search), population of solutions (genetic algorithm) and neighborhood search. For instance, [82] describes a metaheuristic combining elements of GRASP and tabu search to solve large instances of the design of districts for delivery and collection operations. Specific heuristic methods are also frequently used such as the case of multi-phase heuristics [83], greedy heuristic [84], and heuristics based on column generation [85].

Few studies in the literature have addressed districting decisions in milk collection (nine documents in the last ten years). Only two of those papers consider the location-allocation of collection center decisions [18],[27]. The formulation is mono-objective in all works. Where, cost, distance, or utility have been identified as being the feature most considered in the objective function. While the constraints are mainly focused on the vehicle capacity, vehicles without compartments, homogeneous or heterogeneous fleet, plant requirements, no-load division, and milk quality types.

Generally authors use a "cluster first-route second" to tackle the problem, in [12] the authors used that approach to maximize profit for a collection process in southern Chile, considering three milk types of quality, a minimum volume requirement for each type. Similarly, in [18] the authors address the milk collection problem bearing in mind milk types qualities and add location-allocation collection center decisions within the logistics network, first locate the collection centers and second assign the farms to them so small producers can store the milk in these points through an ad-hoc coverage model.

3.3 Mathematical Programming Model Solution Approach

This section propose a districting model that follows a location-allocation structure based on the works of Kalcsic [17] and Bennett [72].

Let **N** be a set of farms, **K** a set of candidate locations for collection centers, **C** a set of collection center types (of different sizes) and **V** a set of vehicle types. The distance between farm $\boldsymbol{i}$ and location $\boldsymbol{k}$ and is $\boldsymbol{d_{ik}}$. Each farm $\boldsymbol{i}$ in **N** has a daily production of milk $\boldsymbol{o_i}$ measured in liters of milk. Each collection center of size $\boldsymbol{c}$ has an operation cost $\boldsymbol{occ_c}$ and a capacity $\boldsymbol{capc_c}$ measured in liters of milk. Furthermore, each vehicle type has a cost of operation $\boldsymbol{ovc_v}$ and a capacity $\boldsymbol{capv_v}$ measured in liters of milk.

Let $\boldsymbol{y_{ck}}$ be binary variables equal to 1 if a collection center of size $\boldsymbol{c}$ is opened in candidate location $\boldsymbol{k}$. $\boldsymbol{x_{ik}}$ be binary variables equal to 1 if farm $\boldsymbol{i}$ is allocated to the collection center in candidate location $\boldsymbol{k}$, this variable is only created for farm-collection center pairs that are within the maximum distance ($x_{ik}\ i \in \mathrm{N},\ k \in \mathrm{K}\ /\ d_{ik} \leq d_{max}$). And $\boldsymbol{w_{vk}}$ be non-negative integer variables that define the number of vehicles of type $\boldsymbol{v}$ allocated to the collection center in candidate location $\boldsymbol{k}$.

Continuous variable $\boldsymbol{u_k}$ represents the capacity utilization percentage of the collection center in candidate location k, which is zero if not location center is opened in k. In order to calculate $\boldsymbol{u_k}$, the variables $\boldsymbol{u_{ck}}$ represent the capacity utilization percentage for each possible size c, where at most one of them is different from zero. Finally, variables $\boldsymbol{umax}$ and $\boldsymbol{umin}$ are, respectively, the maximum and minimum capacity utilization percentage among all opened collection centers.

The problem is to develop a set $\boldsymbol{l}$ of compact districts, one for each collection center in operation, such that workload (i.e., capacity utilization) is balanced across collection centers (i.e., districts). Workload is balanced if the difference between capacity utilization of each pair of collection centers in operation is within an allowable limit, namely is less than a balance threshold $\boldsymbol{\beta_c}$, where $0 \leq \boldsymbol{\beta_c} \leq 1$. Fleet is efficiently used if the percentage of capacity used is greater than a target specified by parameter $\boldsymbol{\beta_v}$, where $0 \leq \boldsymbol{\beta_v} \leq 1$. Distance from farm $\boldsymbol{i}$ to collection center in candidate location $\boldsymbol{k}$ cannot exceed a maximun distance allowed $\boldsymbol{d_{max}}$.

Two objectives are considered. First, the compactness, which is measured as the minimization of the sum of the distances between farms and their allocated collection center. Second, the total operation cost, which is measured as the minimization of the aggregated operation cost of the collection centers and the vehicle fleet.

Hence, the districting model with location-allocation of collection centers decisions can be state as follows:

$$F.O\ \ Min\, distance\ = \sum_{i\,\in\, N} \sum_{k\,\in\, K} d_{ik} x_{ik} \tag{1}$$

$$Min\ Total\ cost\ = \sum_{c\in C}\sum_{k\in K} occ_c y_{ck} \quad + \sum_{v\in V}\sum_{k\in K} ovc_v w_{vk} \qquad (2)$$

S.A

$$\sum_{k\in K} x_{ik} = 1 \qquad \forall\, i \in N\,.\ (3)$$

$$\sum_{c\in C}\sum_{k\in K} y_{ck} = l \qquad (4)$$

$$\sum_{c\in C} y_{ck} \le 1 \qquad \forall\, k \in K\,.\ (5)$$

$$x_{ik} \le \sum_{c\in C} y_{ck} \qquad \forall\, i \in N, \forall\, k \in K.\ (6)$$

$$\sum_{i\in N} o_i * x_{ik} \le \sum_{c\in C} capc_c * y_{ck} \qquad \forall\, k \in K.\ (7)$$

$$u_{ck} \ge \frac{\sum_{i\in N} o_i * x_{ik}}{capc_c} - m\,(1 - y_{ck}) \qquad \forall\, c \in C\,, \forall\, k \in K.\ (8)$$

$$u_{ck} \le \frac{\sum_{i\in N} o_i * x_{ik}}{capc_c} + m\,(1 - y_{ck}) \qquad \forall\, c \in C\,, \forall\, k \in K\ (9)$$

$$u_{ck} \le y_{ck} \qquad \forall\, c \in C\,, \forall\, k \in K.\ (10)$$

$$u_k = \sum_{c\in C} u_{ck} \qquad \forall\, k \in K.\ (11)$$

$$u_{max} \ge\ u_k \qquad \forall\, k \in K.\ (12)$$

$$u_{min} \le u_k + \left(1 - \sum_{c\in C} y_{ck}\right) \qquad \forall\ \ k \in K.\ (13)$$

$$Umax - Umin\ \le \beta_c \qquad (14)$$

$$\sum_{v\in V} capv_v * w_{vk} \ge \sum_{i\in N} o_i * x_{ik} \qquad \forall\, k \in K.\ (15)$$

$$\beta_v * \sum_{v\in V} capv_v * w_{vk} \le\ \sum_{i\in N} o_i * x_{ik} \qquad \forall\, k \in K\ (16)$$

$$y_{ck} \in \{0\,,1\} \qquad \forall\, c \in C\,, \forall\, k \in K\,.\ (17)$$

$$x_{ik}\ \in \{0\,,1\} \qquad \forall\, i \in N, \forall\, k \in K\,.(18)$$

$$w_{vk} \in \{Z^*\} \qquad v \in V, \forall\, k \in K.\ (19)$$

$$0 \le u_{ck} \le 1 \qquad \forall\, c \in C\,, \forall\, k \in K.\ (20)$$

$$0 \le u_k \le 1 \qquad \forall\, k \in K.\ (21)$$

$$0 \leq umax \leq 1 \quad (22)$$

$$0 \leq umin \leq 1 \quad (23)$$

The objective function (1) favors compactness by minimizing the sum of the distances from farms to collection centers. The objective function (2) minimizes the total cost defined as the sum of the cost of opening the collection centers and the operation cost of the vehicles allocated to collection centers. Constraints (3) ensure each farm is allocated to only one collection center. Constraint (4) guarantees the number of collection centers in operation is equal to the number of districts to be designed ***l***. Constraints (5) state that maximum one collection center of any size can be allocated at each candidate location. Constraints (6) ensure farms are allocated to collection centers in operation. Constraints (7) ensure the sum of milk supply of the farms allocated to a collection center does not exceed its capacity. Constraints (8), (9) and (10) determine the percentage of capacity utilization of the collection center of size ***c*** opened in location ***k***, where ***m*** is equal to the maximum capacity of the collection center types. The utilization is zero if no collection center of size ***c*** is located at ***k***. Constraints (11) use the percentage of utilizations calculated for each possible size of the collection center to determine the actual utilization of the collection center opened in location ***k***. Inequalities (12) and (13) computes, respectively, the maximum and minimum utilization among all collection centers in operation, also the second term of the righ-hand side of constraint (13) makes redundant this constraint when there is no a collection center in location ***k***. To balance the workload of the districts, expression (14) ensures the deviation between the percentages of capacity utilization does not exceed the threshold defined in parameter ($\boldsymbol{\beta_c}$). Constraints (15) guarantee that the sum of the capacity of the vehicles allocated to a collection center is enough to serve the milk supply assigned to it. Inequalities (16) ensure that the utilization of the fleet is at least $\boldsymbol{\beta_v}$. Finally, the expressions from (17) to (23) define the domain of the decision variables in the model.

In the literature, there is a vast collection of multi-objective optimization techniques, a review of the main techniques and their applications in engineering is presented in [86]. These methods can be classified into categories: methods that articulate the preferences, which can be done *a priori* or *a posteriori*, and methods with no articulation of preferences on objectives [86]. In order to select the method to tackle the multi-objective problem, it is important to consider factors such as available time, problem complexity and level of accuracy required in the solution [87].

One of the most common methods to tackle the multi-objective problem and get the pareto optimal set is the ε-constraints method also called tradeoff approach. It was first introduced by Haimes, Lasdon, and Wismer in 1975 [88]. The ε-constraints method typically consists in transforming a multi-objective model into a single objective model, by defining the single most important objective function and adding constraints by each one of others objective function related to a set of parameters called epsilon (ε) [87].

The general formulation of ε-constraints method is posed as follows:

Find: $x \in E^n$

To minimize $F_s(x)$

Subject to: $F_i(x) \leq \varepsilon_i, \quad \forall\, i = 1, 2, 3, \ldots, m\ i \neq s$

$g_j(x) \leq 0, \quad \forall\, j = 1, 2, 3, \ldots, k$

However, values of ε must be selected with care, improper selection of ε can lead to an infeasible problem [86]. Also, they can generate weakly Pareto optimal solutions. In the literature, one alternative useful to avoid this problem was introduced by Ehrgott y Ruzika [89], called augmented ε-constraints method.

The general formulation of the augmented ε-constraints method is proposed as follows:

Find: $x \in E^n$

To minimize $F_1(x) - \alpha * \sum_{i=2}^{m} \frac{S_i}{r_i}$

Subject to: $F_i(x) + S_i \leq \varepsilon_i, \quad \forall\, i = 1, 2, 3, \ldots, m$

$g_j(x) \leq 0, \quad \forall\, j = 1, 2, 3, \ldots, k$

Note, that in this case excess variables are used in constraints related to objective functions. These excess variables are included in the objective function and penalized by parameter α, allowing the solver to optimize the main objective function and simultaneously at a lesser extent, optimize the other objective functions for the given epsilon parameters [87],[89]. In the current work, we used the augmented ε-constraints method to tackle the proposed districting model with location-allocation of collection centers decisions under a bi-objective approach.

To implement the model, we used Python with package PYOMO [90], and used a commercial optimizer to solve the problems (Gurobi) [91]. Due to the slow convergence for some instances (making the solution time excessive), the solver (Gurobi) was set to stop when reaching an optimality gap of 3% instead of its default value of 0.01%. The models were run on a laptop with a 2.1 GHz AMD Ryzen 5 processor, Radeon Vega mobile gfx graphic card and 8 GB of RAM.

3.4 Case Study

This section presents the case study used to validate the model, which is based on the dairy cluster of Atlántico, a northern state of Colombia. In 2018 the agricultural sector accounted for 2% of department gross domestic product (GDP) [92] and it is prioritized as a strategic approach for economic, social and environmental development, in its development plan 2020 – 2023 [5].

3.4.1 General description

Atlántico is divided into 23 municipalities, furthermore, these municipalities are grouped into 5 subregions as shown in Figure 10. According to the Colombian Agricultural Institute (ICA), in 2018 Atlántico has recorded 5.885 farms intended for cattle herd activity, 62% of them are intended for milk production [93],[94]. ICA classifies the farms in four categories as a function of the total cattle herd (heads of cattle), that is, small (1-50), medium (51-100), large (101-500) and very large (501 or more), where 82% of farms are small. A total cattle herd of 217.003 heads was reported in Atlántico [95]. These cattle herd generate a daily average milk production of 250.000 liters [96]. Table 6 summarizes the distribution of cattle and milk production in the Department.

Figure 10. Politic Map of Atlántico Subregions.

Subregion	Municipality	Farms	Total cattle herd	1-50	51-100	101-500	501 or more
Metropolitan Area	Barranquilla	37	866	89%	11%	0%	0%
	Galapa	124	4004	78%	14%	8%	0%
	Malambo	129	4691	84%	6%	10%	0%
	Puerto Colombia	2	75	50%	50%	0%	0%
	Soledad	41	3374	54%	22%	22%	2%
	Subtotal	333	13010	78%	12%	10%	0%
Coast	Juan de Acosta	273	7435	88%	8%	4%	0%
	Piojo	224	8610	83%	8%	8%	0%
	Tubara	173	6385	84%	8%	8%	1%
	Subtotal	670	22430	85%	8%	6%	0%
Center	Baranoa	255	11397	76%	11%	13%	0%
	Luruaco	267	10777	84%	7%	9%	0%
	Polonuevo	157	5129	80%	11%	9%	0%
	Sabanalarga	820	36574	79%	10%	10%	0%
	Usiacuri	131	7188	79%	9%	9%	2%
	Subtotal	1630	71065	79%	10%	10%	0%
East	Palmar de Varela	154	4758	84%	8%	7%	0%
	Ponedera	266	17130	65%	17%	17%	1%
	Sabanagrande	95	4389	75%	11%	15%	0%
	Santo Tomas	148	5630	76%	14%	9%	0%
	Subtotal	663	31907	74%	13%	13%	0%
South	Candelaria	336	13049	82%	10%	8%	0%
	Campo de la Cruz	587	14826	91%	6%	3%	0%
	Manati	657	21003	87%	10%	3%	0%
	Repelon	436	11947	89%	7%	3%	0%
	Santa Lucia	393	10536	88%	8%	4%	0%
	Suan	180	7230	81%	12%	7%	1%
	Subtotal	2589	78591	87%	8%	4%	0%
Total		5885	217003	83%	10%	7%	0%

Table 6. Classification and distribution of farms and total cattle herd by subregion [93].

In interviews with managers and workers from companies in the dairy sector of Atlántico, we established the flow and process of milk collection. Initially, the raw milk produced is stored in milk churns (98% of farms) or milk cooling tanks (2% of farms) for preservation. Then, there are a set of routes that establish the collection times for each farm. In the first stage, the raw milk is collected and transported to the collection center either by trucks in milk churns or tanker trucks if the farm has a milk cooling tank. Once the milk arrives at the collection center, it is subject to acidity and fat tests before being cooled. If the raw milk has a percentage of acidity or fat greater than the acceptable limits, it is separated and sent to processing plants to produce mainly powdered milk. Later, generally in the evening hours, once the raw milk from several routes is collected at the collection center, it is transported by tanker trucks to processing plants where it is processed into different derived products for its sale. Figure 11 shows the raw milk flow scheme in the dairy cluster of Atlántico, Colombia.

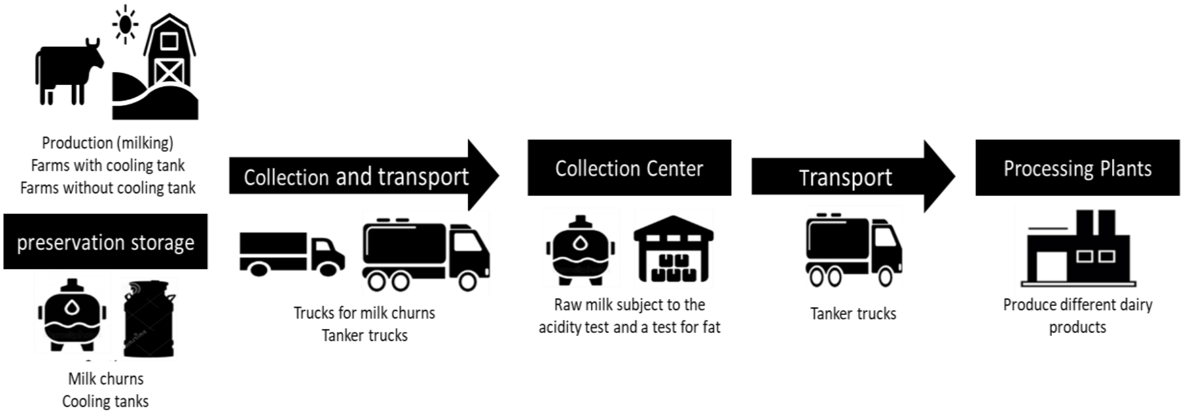


Figure 11. Raw milk flow scheme in the dairy cluster of Atlántico, Colombia.

The milk collection process is usually performed by processing companies. Nevertheless, in some cases, the farmer transports the raw milk to the collection center. The milk collection is performed once a day, although during the dry season it can take place every other day. The trucks used in the operation can carry up to 4000 liters of raw milk (100 churns of 40 liters each). Meanwhile, the tanker trucks can transport 12.500 liters of raw milk. Further details of milk collection process flow are given in the Appendix J.

3.4.2 Case study instance in the dairy cluster of Atlántico

To create the case study, data was collected related to farms, vehicles, collection centers and candidate locations. In addition, the parameter values were selected.

Farms: The instance was set up with 3589 farms, which is approximately the number of farms dedicated to the production of milk in the Department. The number of farms in each municipality was calculated based on the distribution and classification of the 5.885 farms dedicated to cattle herd activity, not all of them are devoted to the production of milk. For instance, Table 7 shows the case for the municipality of Baranoa which holds the 4.33% of the 5.885 farms, hence it would have 4.33% of the 3589 farms dedicated to milk production. Similarly, the milk production by municipality was calculated as a proportion of the average daily production. Considering the number of farms of each size in each municipality, milk production was distributed among the farms such that the larger the farm the larger the amount of milk produced.

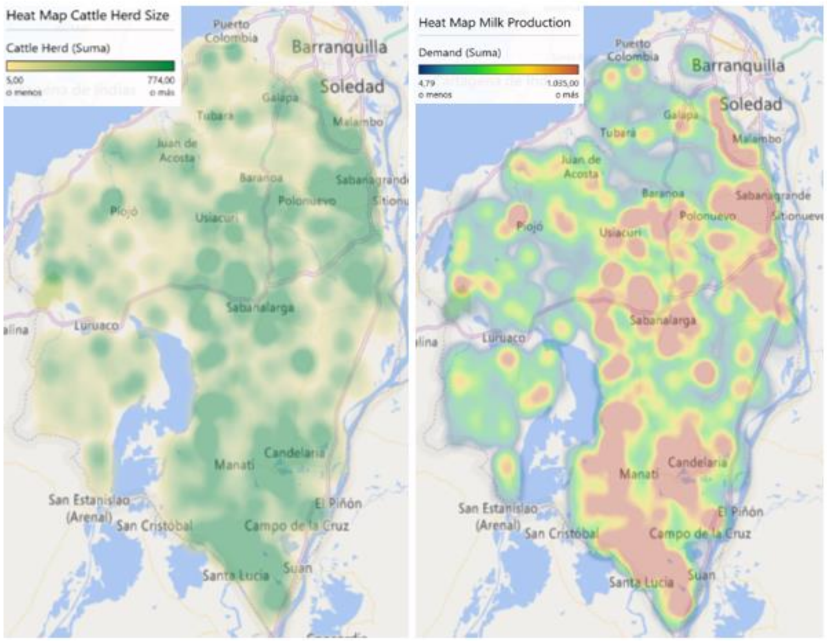
Baranoa contain 4,33% of famrs in Atlantico State

5885 Farms						
Municipality	Farms	Total cattle herd	1-50	51-100	101-500	501 or more
Baranoa	255	11397	193	29	33	0

3589 Farms						
Municipality	Farms	Total cattle herd	1-50	51-100	101-500	501 or more
Baranoa	156	4241	118	18	20	0

Table 7. Example amount of agricultural product units in 3589 farms instance.

Related to the geolocation of each farm, an official record of this data was not found due to the confidentiality of this information. Therefore, the geolocation data was generated randomly within each subregion taking care that farms do not overlap among them, to the municipality, lakes, or rivers. The distribution of farms and milk production is uneven in the territory of the state, there are a greater number of farms and milk production in the center and south of Atlántico state in municipalities such as Sabanalarga, Candelaria, Manti, Unsecure, Polonuevo, Campo de la Cruz, Santa Lucia, as shown in Figure 12.



Municipality	Demand	Cattle Herd
Baranoa	5,3%	5,5%
Barranquilla	0,4%	0,4%
Campo de la Cruz	6,8%	7,2%
Candelaria	6,0%	5,5%
Galapa	1,8%	2,1%
Juan de Acosta	3,4%	3,8%
Luruaco	5,0%	5,3%
Malambo	2,2%	2,9%
Manati	9,7%	8,1%
Palmar de Varela	2,2%	2,5%
Piojo	4,0%	4,1%
Polonuevo	2,4%	2,8%
Ponedera	7,9%	6,5%
Puerto Colombia	0,0%	0,0%
Repelon	5,5%	5,6%
Sabanagrande	2,0%	2,0%
Sabanalarga	16,9%	16,5%
Santa Lucia	4,9%	5,2%
Santo Tomas	2,6%	2,9%
Soledad	1,6%	1,4%
Suan	3,3%	3,1%
Tubara	2,9%	3,4%
Usiacuri	3,3%	3,2%

Figure 12. Farms and milk production share.
Milk production in liters and cattle herd in units.

Vehicles are the transport method to be used to collect raw milk on farms and transport it to the collection centers. Three types of vehicles were considered each of them with a different capacity measured in liters, that is, 3500 (87 milk churns), 4000 (100 milk churns) and 5000 (112 milk churns). The vehicle acquisition cost is based on the value of a new truck, namely, US$22.368, US$25.000, US$27.105, respectively.

Collection centers are the facilities used to temporarily store raw milk before transporting it in refrigerated vehicles to processing plants. We considered six sizes of different capacities, that is, 10000, 20000, 30000, 50000, 70000 y 90000 liters of milk. The facility cost is based on the standard cost calculated by the National Department Planning of Colombia [97]. This cost includes an estimation of the investment stage (construction and endowment) and operational stage (annual maintenance and operation), see Table 8.

Collection Center type		
id_	Capacity_	Cost
1	10000	US$ 230.119
2	20000	US$ 258.262
3	30000	US$ 286.405
4	50000	US$ 342.691
5	70000	US$ 398.977
6	90000	US$ 455.264

Table 8. Collection center type.

Candidate locations are the potential geolocation for the collection centers within the milk collection network. According to the advice of stakeholders, FAO, and National Department Planning of Colombia, a collection center should be in a location close to reliable sources of clean water and other utilities, close to the road, accessible to milk transport vehicles, and allow to easily construct a building [98]. Hence, a potential candidate location is identified in each municipality (23) of Atlántico state. In Barranquilla, the candidate location is the current location of the processing plant of the biggest company in the dairy sector. Thus, it is considered a collection center adjacent to the processing plant.

In the current work the Haversine distance is used to calculate distances between each farm to each candidate location. The Haversine distance has been shown to be a good approximation in transport problems context such as vehicle routing problem (VRP) instead of real road distance [99].

Further details about the instance are provided in Appendix k (available online https://acortar.link/hQHry6).

3.5 Computational and Numerical Experiments

The numerical experiments are focused mainly in four parameters, namely, the number of collection center to be opened (L), maximum distance allowed from a farm to the allocated collection center (d_{max}), fleet usage ratio (β_v) and max deviation between capacity utilization of collection centers open to operation (β_c).

The number of collection center to be open (l) allows to identify the point at which more collection centers do not generate a significant improvement (decrease) in distance. The parameter d_{max} is set initially to 30km because, according to the FAO and other studies in the sector, the distance from a farm to a collection center should not exceed that distance. The maximum running time of the optimizer for any run was set to 60 min. The fleet usage ratio is calculated for each collection center to avoid overuse vehicles in one collection center and underuse vehicles in others. The larger the value of β_v, the greater the pressure for an efficient use of the fleet. The parameter β_c seeks for an equitable distribution of workload among districts, specific the maximum difference between workload among districts. The smaller the value, greater the balance. Therefore, to induce the greater balance a parameter value of 0.05 while a value of 1 deactivates the constraint. The percentual utilization is used instead of the total load as the geographical distribution of customers might not be uniformly within the operation area.

Parameters Levels							
β_v	0.01	0,7	0.8	0.9	0.95		
β_c	1	0.2	0.15	0.1	0.05		
dmax	30	25	20	15	10		
L	23	19	14	9	7	5	3

Table 9. Parameter Levels - Experiments.

Table 9 details the proposed parameter values considering four model parameters. In total, we executed 1211 experiments as the results of the different combinations of the level of the parameters.

The solutions are evaluated through the objective functions, that is, distance and cost. Additionally, some other metrics are calculated to get insights about the quality of the solutions, such as: the maximum distance between all farms and their allocated collection center, utilization capacity range, the spatial distribution of collection centers and farms, and the slack in the utilization of the capacity of the collection centers.

The analysis of the experiments consists of four parts. The first set of experiments helps to determine the number of collection centers from which the average distance between farms and collection centers converges. Given the ideal number of collection centers, the second set of experiments studies the impact of the maximum distance and the balance on the usage of the resources (i.e., capacity of the collections centers and fleet of vehicles) considering the tradeoff between distance and cost objectives. The third part of the analysis focuses on the structure of the solutions to draw insights for the milk collection network design. Finally, the last part of the analysis describes a proposed structure for the milk collection network in the Atlántico state.

3.5.1 Number of collection center ($\boldsymbol{l}$).

When increasing the number of collections centers the cost increases while the average and maximum distances decrease. As shown in Figure 13, when opening seven collection center the average and maximum distance converges such that a new collection center would not improve these metrics but adding it would impact significatively the total cost. In a collection network with seven collection centers the average and maximum distance between farms and their allocated collection center are 3.88 km and 9.77 km, respectively. The latter is even less than the third part of the standard suggested by FAO (i.e., 30 km).

Table 10 details the result comparison vs seven collection centers in milk collection network, these results highlighted that it is not worth open more than 7 collection center because there will not be a substantial decrease in the average distance between producer and collection centers between 8% and 22%, compared to the increase in cost between 12% and 93%. Whereas open fewer collection centers significantly increase the average distance between 19% and 89%.

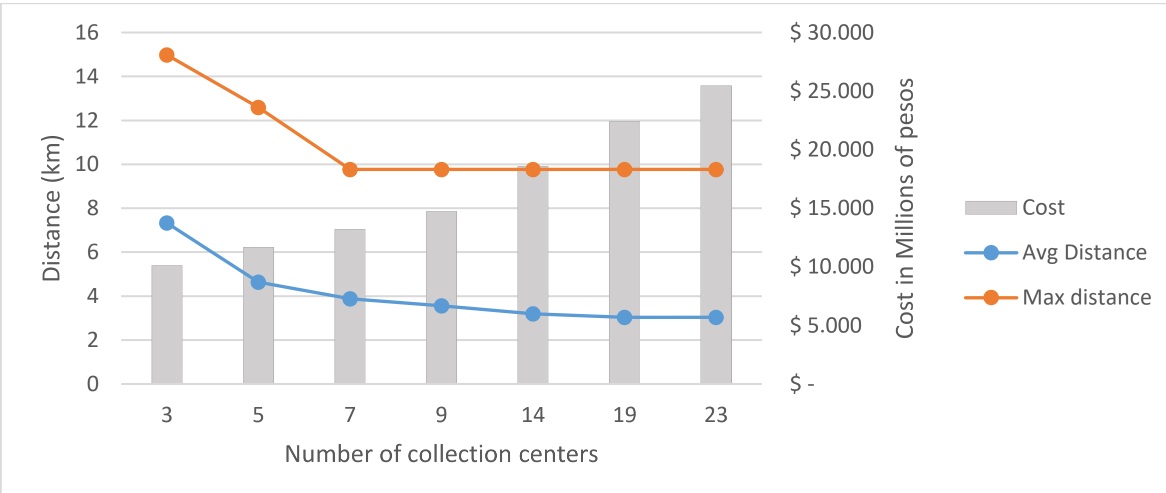


Figure 13. Avg distance, Max distance and Cost vs Number of collection Center in 3589 farms - instance.

Data				FAO	Avg distance	Max distance	Cost
Collection centers	Avg distance	Max distance	Cost	Max distance Vs Standard	Δ Avg 7	Δ MaxD 7	Δ Cost 7
3	7,33	14,98	$ 10.126	50%	89%	53%	-23%
5	4,63	12,59	$ 11.661	42%	19%	29%	-12%
7	3,88	9,77	$ 13.196	33%	0%	0%	0%
9	3,56	9,77	$ 14.731	33%	-8%	0%	12%
14	3,19	9,77	$ 18.569	33%	-18%	0%	41%
19	3,04	9,77	$ 22.406	33%	-22%	0%	70%
23	3,04	9,77	$ 25.476	33%	-22%	0%	93%

Table 10. Avg distance, Max distance and Cost comparison vs seven collection center.

3.5.2 Distance – Cost Trade Off.

Based on the previous results we set the number of collection centers in the Atlántico milk collection network in seven, and the maximum distance parameter (d_{max}) in 10km. We now focus on the cost objective to study the trade-off between both objectives and find the best economic (cost) configuration (structure) without worsening the distance objective. Further experiments summarized in Table 11, show that when the maximum distance parameter is set to 10km, a minimum fleet usage ratio of vehicles allocated to each collection center (β_v) equals to 0.8 is interesting as it generates good solutions in terms of average and maximum distance.

Bv	Bc	time_seg	avgdistance	Max distance	Unbalance	avg holgura	Max Holgura	Min Holgura	Costo
0,8	1	34,69	3,883308	9,77	74%	42861	74743	4746	$ 17.629.461.862
0,8	0,2	46,87	3,883551	9,77	20%	40004	57221	14743	$ 17.511.574.498
0,8	0,15	54,17	3,883308	9,77	14%	25718	40001	14743	$ 16.756.137.678
0,8	0,1	77,22	3,883562	9,77	10%	25718	39188	14043	$ 16.297.137.678
0,8	0,05	206,95	3,885227	9,77	5%	25718	38867	13207	$ 16.441.137.678

Table 11. Interaction analysis between balance and fleet usage β_v vs β_c.

To highlight the impact of the constraints that balance the utilization of the capacity at the collection centers, the model is first run deactivating those constraints and prioritizing the distance objective. As a result, collection centers with the largest capacity are opened no matter the capacity rate utilization. Figure 14 shows that this scenario generates over cost by using collection centers of 50,000 liter capacity or more in all candidate locations, while generates an average slack capacity of 40,000 liters and underusage of collection centers capacity, being the minimum utilization 17% and the maximum 91%.

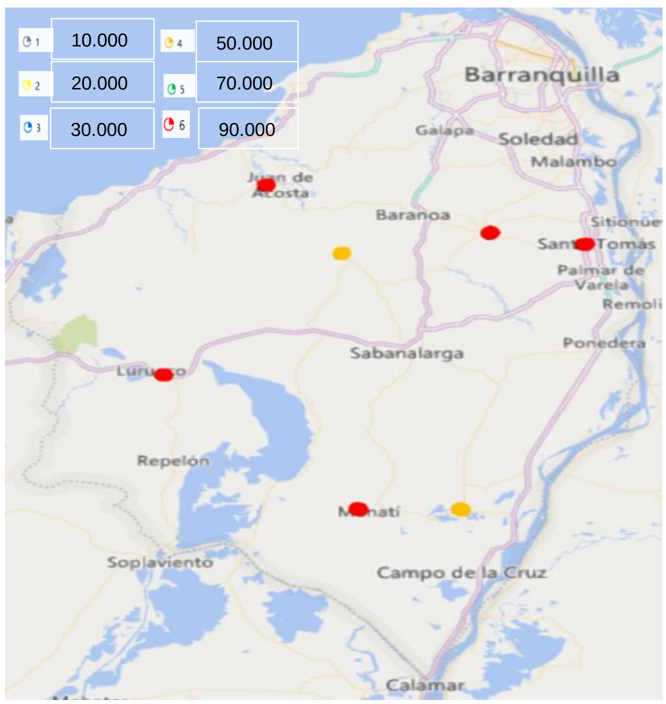


Figure 14. Solution without balance in the capacity utilization of the collection centers. Collection center capacities in liters.

The observed performance of the solution was improved by considering the balance constraints. When the balance of the used capacity at the locations centers is set to 5%, the facilities are located in the same municipalities, as shown in Figure 15, but the installed capacity is smaller and the farms are reallocated to those lower and medium size collection centers to comply with the balance constraint, which in turns generates a 7% cost savings. This demonstrates how important balance constraint is in capacity utilization and economic terms.

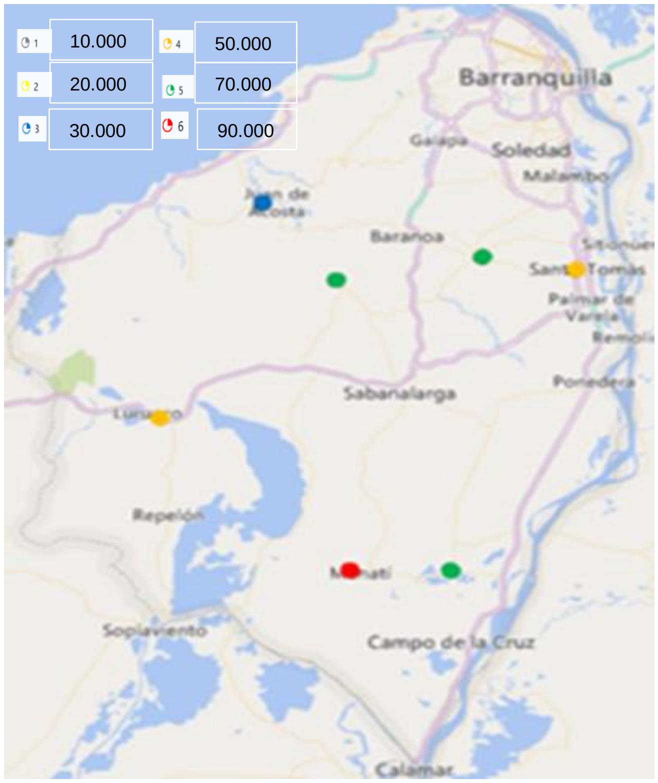


Figure 15. Solution with balance in the capacity utilization of the collection centers. Collection center capacities in liters.

We now focus on the cost objective to study the trade-off between both objectives and find the best economic (cost) configuration (structure) without worsening the distance objective. To evaluate the tradeoff between distance and cost objectives, the augmented ε-constraints method was used, with α = 0.1. The cost objective was given priority, using distance as a constraint, this results the Pareto frontier shown in Table 12 and Figure 16.

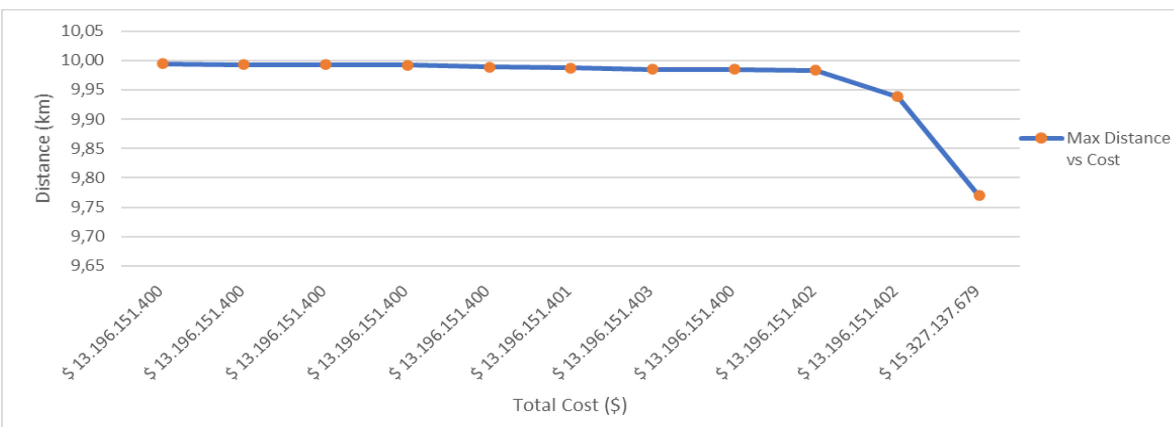


Figure 16. Solution frontier Max distance and Cost in 3589 farms – instance, Atlántico State.

Even when the average distance between a farm and its collection center is an objective of the model, the maximum distance was used to analyze the tradeoff between cost and distance. This is because the maximum distance is more informative in the context of compactness. The maximum distance allows us to understand what is the radius of a zone.

Experiment	Cost	Avgdistance	Max distance	Unbalance	Avg slack capacity (L)	Max slack capacity (L)	Min slack capacity (L)
1	$ 13.196.151.400	5,44	9,99	0,00	4,14	10,00	0,00
2	$ 13.196.151.400	5,35	9,99	0,00	4,14	21,00	0,00
3	$ 13.196.151.400	5,27	9,99	0,00	4,14	17,00	0,00
4	$ 13.196.151.400	5,24	9,99	0,00	4,14	15,00	0,00
5	$ 13.196.151.400	5,02	9,99	0,00	4,14	18,00	0,00
6	$ 13.196.151.401	4,66	9,99	0,00	4,14	16,00	0,00
7	$ 13.196.151.403	4,61	9,99	0,00	4,14	28,00	0,00
8	$ 13.196.151.400	4,47	9,99	0,00	4,14	11,00	0,00
9	$ 13.196.151.402	4,27	9,98	0,00	4,14	11,00	0,00
10	$ 13.196.151.402	4,08	9,94	0,00	4,14	12,00	0,00
11	$ 15.327.137.679	3,89	9,77	0,05	25718,43	39267	13207

Table 12. Pareto frontier points – experiments results.

The trade-off between distance and cost is clear as the greater the distance, the lesser the cost. When lower and medium size collection centers are opened, which reduces the cost, farms are reallocated to distant collection centers to comply with the balance constraint, which increases the total distance. Comparing the two extremes of the pareto frontier shows that we can decrease the cost by 16%, considering a maximum distance increase of 2,3% (0,22km). Further analysis showed that if slack is required in the storage capacity of the collection centers, larger collection centers (70,000 or 90,000 liters of milk) should be used in four of the seven locations (60% of cases). Otherwise, using smaller collection centers (50,000 liters milk or less) in five of the seven locations (79% of cases) generates lesser slack in the capacity of the collection centers i.e., less room for growth of the operation. However, it is important to note that cost does not significatively varies because the strong cost component related to the number of collection centers open is partially fixed (7 collection centers), see Figure 17. Furthermore, the results show that fleet component is less relevant because there is only a minimum fleet usage percentage (v) requirement and not a maximum requirement. Thus, the fleet usage in all solutions tends to close to 100%, decreasing the number of vehicles and impact on cost.

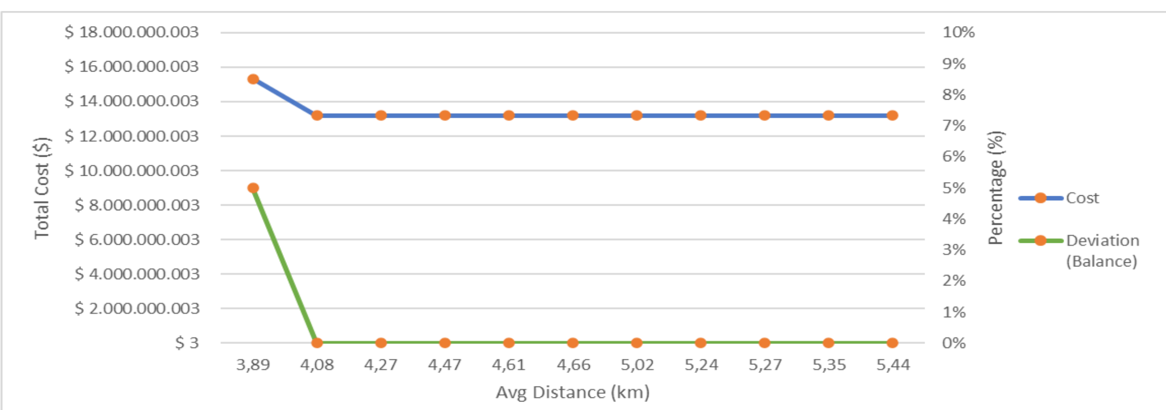


Figure 17. Solution frontier Avg distance and Cost in 3589 farms – instance, Atlántico State.

3.5.3 Structural analysis of solutions.

The analysis in this section is based on the solutions in the efficient frontier of the case study. They are, therefore, obtained without any change in the parameters of the model. To draw insights about the structure of the solutions, in Table 13 we count the number of times a given collection center is located in a municipality and the capacity size that is assigned. Additionally, the farm share is the average percentage of farms allocated to the operating collection center in each municipality based on the set of solutions of the multi-objective model.

Data				Collection Center					
Municipality	Events	Frecuency	Farm Share	10	20	30	50	70	90
Luruaco	11	100%	13%	27%	0%	64%	9%	0%	0%
Usiacuri	11	100%	11%	45%	18%	9%	18%	9%	0%
Manati	10	91%	34%	0%	0%	0%	10%	50%	40%
Candelaria	8	73%	13%	50%	25%	13%	0%	13%	0%
Santo Tomas	8	73%	11%	38%	13%	13%	38%	0%	0%
Polonuevo	7	64%	19%	0%	14%	0%	29%	57%	0%
Juan de Acosta	6	55%	9%	50%	0%	50%	0%	0%	0%
Piojo	5	45%	11%	40%	0%	60%	0%	0%	0%
Baranoa	4	36%	20%	25%	0%	0%	25%	50%	0%
Sabanalarga	3	27%	23%	33%	0%	0%	0%	33%	33%
Ponedera	3	27%	19%	0%	0%	0%	100%	0%	0%
Santa Lucia	1	9%	22%	0%	0%	100%	0%	0%	0%

Table 13. Structural analysis of multi-objective solutions.

These results revealed that in all the solutions there are collections centers located at Luruaco and Usiacurí. In most cases, the collection center at Luruaco has a capacity of 30.000 liters, its groups on average 13% of the farms, mainly in the eastern of the state. In Usiacurí, the opened collection center has in most cases a capacity of 10.000 liters and groups on average 11% of the farms. The smaller capacity assigned to this location center might be due to the fact that in the state central area there is a significant milk production and there are other collection centers also opened in nearby municipalities such as Polonuevo and Santo Tomas.

Additionally, Table 13 and Figure 18 show that is relevant to have a collection center in municipalities such as Manatí (91%), Candelaria (73%), Santo Tomas (73%), Polonuevo (64 %), Juan de Acosta (55%) and Piojo (45%). In Manatí, it is desirable to have a collection center of 70000 liters to group an average 34% of the farms considering that the south of the state presents a higher density of farms and milk production. Other municipalities, such as Baranoa (36%), Sabanalarga (27%), Ponedera (27%) and Santa Lucia (9%) are options to open a collection center. However, they appear less frequently within the set of solutions. Nevertheless, it is desirable to use collection centers of 30,000 or more liters on average 66% of the time (when they appear), to group on average 20% of farms. Eleven municipalities (Barranquilla, Campo de la Cruz, Galapa, Malambo, Palmar de Varela, Puerto

Colombia, Repelón, Soledad, Suan, and Tubara) should not be considered to locate a collection center, when considering the distance criteria, as they never appeared in the set of solutions.

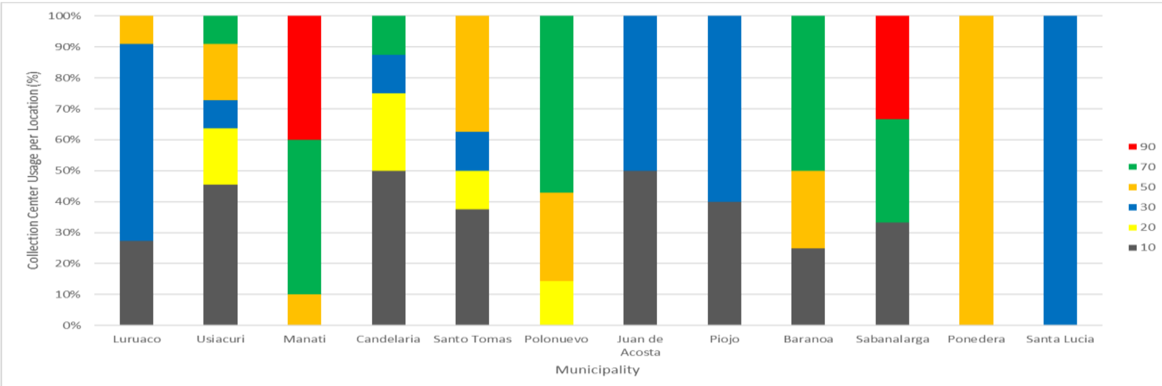


Figure 18. Utilization percentage of each collection center size by candidate location in the solution frontier.

3.5.4 Milk collection network recommended structure.

A solution that uses most of the vehicles and collection centers capacity is worth to study (solution two in pareto frontier). Therefore, we focus on the solution described in Figure 19 and Table 13. In that solution, the cost decreases 16% ($ 2.000.000), the average distance worsens only 5% (0.2km) and maximum distance between a farm and its collection center increases only 1.7% (0.16km) when compared to solution one in Pareto frontier. Furthermore, the results showed a homogeneous fleet composition (50 vehicles of 5000 liters) and a set of collections centers with different sizes but with similar utilization.

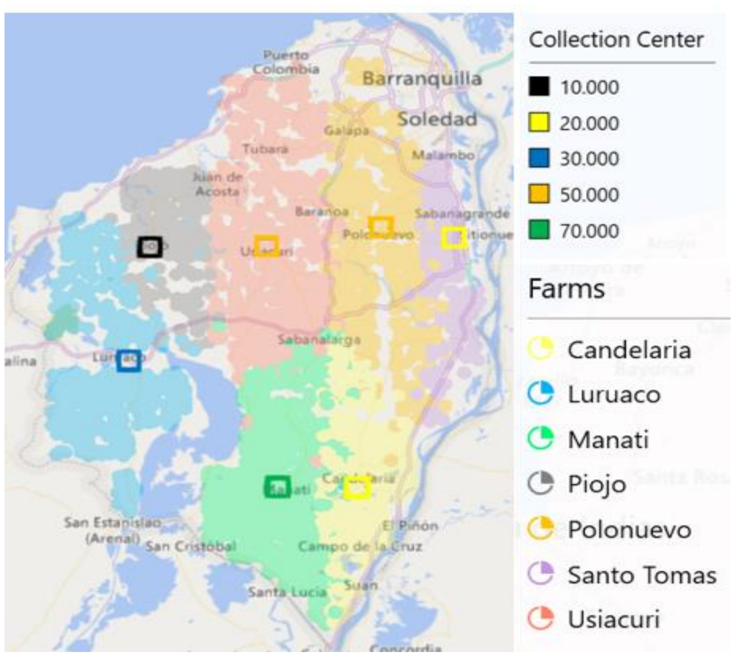


Figure 19. Spatial distribution - Solution two for the milk collection network in the Atlántico state. Collection center capacities and milk production in liters.

Solution 10								
Municipality	Collection Center	Share	Fleet Usage	Capacity Usage	Slack	Vehicles 1	Vehicles 2	Vehicles 3
Candelaria	20.000	17,1%	100,0%	100,00%	0,00%	0	0	4
Luruaco	30.000	14,1%	100,0%	99,94%	0,06%	0	0	6
Manati	70.000	32,7%	100,0%	99,99%	0,01%	0	0	14
Piojo	10.000	7,6%	100,0%	99,98%	0,02%	0	0	2
Polonuevo	50.000	17,8%	100,0%	100,00%	0,00%	0	0	10
Santo Tomas	20.000	10,6%	100,0%	99,99%	0,01%	0	0	4
Usiacuri	50.000	19,9%	100,0%	100,00%	0,00%	0	0	10

Table 14. Solution ten (10) - frontier solutions (structural data).

However, capacity slack in collection centers is an interesting characteristic because it offers the possibility of supporting a seasonal milk production increase or the growth of the operation. Hence, Table 15 shows a solution in which at least 5% of slack capacity is required in each collection center.

Solution 0.05 Bc								
Municipality	Collection Center	Share	Fleet Usage	Capacity Usage	Slack	Vehicles 1	Vehicles 2	Vehicles 3
Candelaria	20.000	13,6%	100,0%	94,99%	5,01%	1	0	3
Luruaco	30.000	11,7%	100,0%	92,44%	7,56%	1	0	5
Manati	70.000	26,7%	100,0%	92,85%	7,15%	0	0	13
Piojo	10.000	6,0%	94,9%	94,99%	5,01%	0	0	2
Polonuevo	70.000	18,0%	100,0%	92,85%	7,15%	0	0	13
Sabanagrande	20.000	7,9%	100,0%	92,50%	7,50%	1	0	3
Usiacuri	50.000	16,1%	100,0%	89,99%	10,01%	0	0	9

Table 15. Recommended structural solution for the milk collection network in the Atlántico state with Slack.

The recommend configuration is shown Figure 20. In this scenario, the milk collection network presents an average capacity slack of 7% and a more equitable distribution of farms to the collection centers. Therefore, to add a capacity slack for each collection center compared with solution two is necessary:

- Modify location of one collection center (same size 20.000 liters) from Santo Tomas to the nearby municipality of Sabanagrande
- Change the size of the collection center located in Polonuevo from 50.000 liters to 70.000 liters.
- Use a type 1 vehicle unit in Candelaria, Luruaco and Sabanagrande.

According to the solution that uses all the installed capacity, this solution increases the cost and average distance to collection centers in 2% while the maximum distance to a collection center does not vary. Additionally, the fleet composition is homogeneous, and its capacity is used almost at 100%.

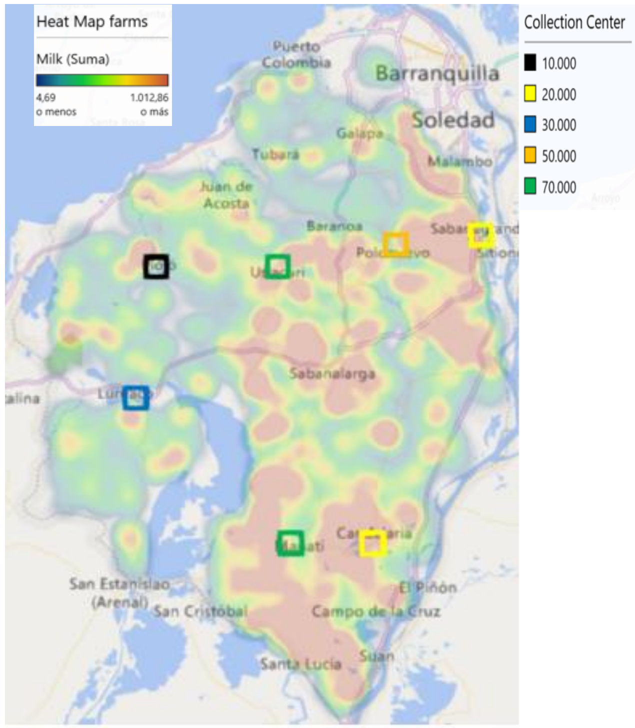


Figure 20. Recommended structural solution heat map for the milk collection network in the Atlántico state. Collection center capacities and milk production in liters.

3.6 Conclusions of the Chapter

In this chapter, a districting model with location-allocation of collection center decisions was developed to solve the milk collection problem in Atlántico state at strategic-tactical level (case study). Several experiments were evaluated to define structural parameters such as the number of collection center to be open (l), max distance allowed from a farm to a collection center allocated (d_{max}), min fleet usage ratio of vehicles allocated to each collection center (β_v) and max deviation between capacity utilization (balance) of collection centers open to the operation (β_c). Our research is a useful aid for decision-makers because it derives interesting managerial insights and implications for the milk collection network structure in Atlántico state. The experiments that study the combination of parameters combine the parameters are a reliable tool to diagnose or study desirable parameters setting and to analyze the tradeoff between distance and cost objectives.

The results obtained challenge the classical approach to calculate the balance in districting problems as an absolute load. It is possible a cost decrease of 16% ($2.000.000 COP) with a 40% (1,55 km) increase of the average distance between farms and their allocated collection center but with an increase of only 2,3% (0,22km) in the maximum distance.

The trade-off between distance and cost is clear as with greater distance, the cost decreases. However, it is necessary to open lower and medium size collection centers (to reduce the cost) and, in turn, farms are reallocated to distant collection centers to comply with the balance constraint (more distance). Furthermore, the classical approach assumed that customers are evenly distributed geographically, something that is not fulfilled in this real context. A percentage balance of each collection center proves to be effective to obtain an even utilization of the collection centers indistinctly to their size (not overuse a collection center and underuse others). Also, the balance constraint proves to improve the solution in structurally and economic terms.

The computational results show that the model is efficient for finding the optimum solution. The solver found the optimum in the distance context in 4 min on average, and, in 24 min on average for the cost context. The multi-objective approach found a solution in 21 min on average. Also, in 75% of experiments the gap to the optimum was 0%, in 22% of experiments the gap to the optimum was greater than 0 (Avg 1,8%). Finally, in 3% of the experiments the resulting model (with the proposed parameter combination) were infeasible.

Several directions for future studies were identified in this chapter which could serve as a base to introduce tactical or operative decisions in the model, such as production and distribution planning or routing plan. Future studies should include characteristics such as multi-period, stochastic data, time windows in order to make more realistic and to validate the impact of seasonal production variation in the structure (district design) of milk collection networks.

Chapter IV
Concluding remarks

The Colombian dairy sector is subject to several risks from external sources, considering the free trade agreements signed by the country's government recently. Also, several problems and challenges have been identified in the supply chain of the dairy sector, such as inefficiency in the logistics process in milk collection. Hence, it is imperative to increase productivity and reduce operating costs in the dairy sector to guarantee the access of its products to the markets. Undoubtedly, determining efficient operating models and minimizing the impact of producers (farms) atomization on collection distances have gained significatively importance to improve productivity and reduce costs. The proposed methodology and the focus of this study were tackling the milk collection problem at the strategic-tactical level as a districting problem using optimization, with the aim of grouping the farms to minimize the distances to be covered in a subsequent routing (collection). The analysis and results proved that by grouping farms into collection centers it is possible to design a compact and balanced districting with a fair collection center utilization and efficient fleet usage, minimizing the cost and the average distance to be covered in the subsequent milk collection operation.

In Chapter 2, the literature review based on prescriptive analytics to face the milk collection problem, considering four dimensions namely, problem setting, decisions, characteristics/constraints, and methodological approaches gave important insights and relevancy to the current research and clear directions for future studies in the field. This review has led us to conclude that the milk collection problem is an interesting problem to address, considering the strategic, tactical, or operational decisions. The findings of this review support the idea that districting decisions have been addressed frequently recently due to the positive effect that their result generates on subsequent routing.

In chapter 3, a districting model with location-allocation of collection center decisions was proposed to solve the milk collection problem in Atlántico state at strategic-tactical level. The districting model with location-allocation of collection center decisions can be used to design compact and balanced districts with a fair collection center utilization and efficient fleet usage. The case study was designed based on the dairy cluster of Atlántico, considering data from ICA, ASOGANORTE, FEDEGAN, FAO and the national planning department of Colombia. The problem formulation was extended to model the trade-off between distance and cost, first prioritizing distance to find the number of districts to be designed (i.e., the number of collection centers to be open), secondly, we focus on the cost to study the trade-off between both objectives and finally recommend an economic (cost) configuration (structure) without worsening the distance objective.

Several metrics to compare solutions and measure the impact of districting in the structure of the milk collection network were proposed. The evaluation of the set of multiobjective solutions reveal interesting conclusions with useful managerial insights and implications for the milk collection network structure in Atlántico state. One interesting result is the model preference for some candidate location to allocate a collection center, the result suggests that the recommended structure of seven (7) collection centers for the milk collection network (districts) in Atlántico tends to have a robustness independently of the average distance limit. This result has a deep practical usefulness since it clarifies the allocation decisions for the collection center, irrespective of the sizes of the collection center and the possible distance and cost scenarios.

Several directions for future studies were identified: to introduce tactical or operative decisions in the model. A major drawback identified lies in the lack of research joining districting, production, and distribution planning, and/or routing decisions with driver-scheduling decisions in the milk collection context. Also, future studies should address the milk collection problem considering the product aspect due to the interest in including features such as different qualities of the product, allow blending and compartmented transport. Furthermore, future studies should include characteristics such as multi-period, stochastic data, time windows in order to make more realistic and to validate the impact of seasonal production variation in the structure (district design) of milk collection networks. On the other hand, an alternative approach is to address operative decisions like routing problem, to determine the set of vehicle routes and sequence to visit the customers.

Unfortunately, it was not possible access to real data of geolocalization and milk production of each farm in the case study of Atlántico, generating possible sources of bias in the data and analysis. However, the development of optimization models based on location-allocation of collection center decisions in district design stand out as prominent method to brings new insights and strategies to milk collection network structures (district design).

APPENDIX

Appendix A. Taxonomy of milk collection problem.

1. Scenario Characteristics	2. Problem physical characteristics
1.1 Input Data	2.1 Vehicles
1.1.1 Static	2.1.1 Type
1.1.2 Dynamic	2.1.1.1 Homogeneous
1.1.3 Deterministic	2.1.1.2 Heterogeneous
1.1.4 Stochastic	2.1.2 Number
1.2 Problem Context	2.1.2.1 Unlimited
1.2.1 Vehicle routing problem	2.1.2.2 Fixed
1.2.2 Heterogeneous vehicle routing problem	2.1.3 Structure
1.2.3 Milk Collection problem with collection points	2.1.3.1 Compartmentalized
1.2.4 Stochastic dairy transportation problem	2.1.3.2 Not compartmentalized
1.2.5 Periodic vehicle routing problem with time windows	2.1.4 Capacity constraints
1.2.6 Single truck and trailer routing problem with satellite depots	2.1.5 Refrigerated vehicles
1.2.7 Multi-Attribute vehicle routing problem	2.2 Time or distance
1.2.8 Prize-Collecting vehicle routing problem	2.2.1 Time or distance constraints
1.2.9 Vehicle routing problem with simultaneous pick-up and delivery	2.2.2 Uncertainty and vulnerability
1.2.10 Milk collection network location routing problem	2.2.3 Travel, service or waiting time
1.2.11 Milk collection network vehicle fleet mix problem	2.2.4 Dead distance
1.2.12 Multi-Period vehicle routing problem with seasonal fluctuations	2.3 Time window structure
1.2.13 Truck and trailer routing problem	2.2.1 Single time window
1.2.14 Generalized truck-and-trailer routing problem	2.2.1 Multiple time window
1.2.15 Truck and trailer vehicle routing problem	2.4 Incompatibility constraints
1.2.16 Vehicle routing problem with trailers and transshipments	2.5 Specific constraints
1.2.17 Production and distribution planning	2.5.1 Prioritization or Preassignments
1.2.18 Capacitated Vehicle Routing Problem	2.5.2 Environmental
1.2.19 Milk-run vehicle routing problem	2.5.3 Accessibility constraints
1.2.20 Multi-Depot collaborative transportation problem	2.6 Objective function
1.2.21 Annual dairy transportation problem	2.6.1 Single Objective
1.2.22 Supply Chain Management	2.6.2 Multiple objectives
1.2.23 Periodic milk collection problem	2.7 Product Constraints
1.2.24 The scheduling and routing problem	2.7.1 Quality
1.2.25 Milk tanker scheduling and sequencing problem	2.7.2 Flow and mass conservation
1.2.26 Vehicle allocation problem	2.7.3 Blending
1.2.27 Symmetric Travelling Salesman Problem	2.7.4 Not blending
1.2.28 Traveling Salesman problem	2.8 Location
1.2.29 Schedulling problem	2.8.1 Industry or Plant Requirements
1.3 Decision management components	2.8.2 Attention requirement of each farm
1.3.1 Districting or Clustering	
1.3.2 Location	
1.3.3 Production and distribution planning	
1.3.4 Driver scheduling	
1.3.5 Routing	
1.4 Number of depots	
1.4.1 Single depot	
1.4.2 Multiple depots	
1.5 Load splitting constraints	
1.5.1 Splitting allowed	
1.5.2 Splitting not allowed	
1.6 Planning period	
1.6.1 Single period	
1.6.2 Multi-period	
1.7 Multiple Use and special characteristic of vehicles	
1.7.1 Single trip	
1.7.2 Multi-trip	

Appendix B. Problem contexts milk collection problem.

Problem Context	Works	Characteristics
Vehicle Routing Problem	(Caria, Todde, & Pazzona, 2018) - (Paredes-Belmar, Marianov, Bronfman, Obreque, & Lüer-Villagra, 2016) - (Amiama, Pereira, Carpente, & Salgado, 2015) - (Butler, Herlihy, & Keenan, 2005) (Sankaran & Ubgade, 1994)	Single period, fleet capacity, not compartment vehicles, fleet fixed, attention requirement, load not split, homogeneous fleet of vehicles.
Supply Chain Management - Production and distribution planning	(Ghosh & Mondal, 2018) - (Malihi & Aghdasi, 2014) - (Li, Zhang, & Jiang, 2008)	Collection periods, requirement plant, quality, attention requirement, load not split, fleet of vehicles, production scheduling, distribution planing.
Schedulling problem	(Sehulster & Pratt, 1983) - (Kalra & Singh, 1988)	schedulling vehicles, capacity, time constraints, collection frequency pickup.
Traveling Salesman problem	(Dooley, Parker, & Blair, 2005) - (Harrison & Wills, 1983)	single period, capacity, multi trips, fleet fixed, attention requirement, load not split.
Vehicle Collection Problem	(Cegiełła, Szymanowski, & Prokuratorski, 1986)	schedulling vehicles, capacity, time constraints, collection frequency pickup, central depot, fleet of vehicles.
Milk Collection Network Location Routing Problem	(Mumtaz, Jalil, & Chatha, 2014)	Location facilities, allocation customers, routes, attention requirement, capacity, fleet of vehicles.
Milk Collection Network Vehicle Fleet Mix Problem	(Mumtaz, Jalil, & Chatha, 2014)	Vehicles location, routes, capacity.
Milk Collection Problem with blending and Collection Points	(Paredes-Belmar, Lüer-Villagra, Marianov, Cortés, & Bronfman, 2017)	Blending, routes, location facilities, capacity, Location facilities, allocation customers, routes, attention requirement, fleet of vehicles.
Milk-run Vehicle Routing Problem	(Mei, Jingshuai, Teng, Xiuli, & Ting, 2017) - (Basnet, Foulds, & Wilson, 1997)	runs, homogenous vehicles, fleet of vehicles fixed, capacity, assignments runs to tankers, order visit (assignment).
Prize-Collecting Vehicle Routing Problem	(Montero, Canales, Paredes-Belmar, & Soto, 2019)	no attention requirement, plant requirement, minimum requirement, capacity.
Capacitated Vehicle Routing Problem	(O'Callaghan, O'Connor, & Goulding, 2018)	Number of vehicles, capacity, routes, central depot, homogenous vehicles.
Vehicle Routing Problem with Simultaneous Pick-Up and Delivery	(Ruiz, 2018) - (Sethanan & Pitakaso, 2016)	Simultaneous Pick-Up and Delivery, compartments, capacity, not blending, multi trip.
Vehicle Routing Problem with Trailers and Transshipments	(Drexl, 2014)	fleet of heterogeneous vehicles, one depot, transshipment locations, accessibility, time windows, Imcompatibilities.
Multi-Depot Collaborative Transportation Problem	(Lou, Li, Luo, & Dai, 2016)	collaborative transportation route, milk runs, common transport task, transport task allocation.
Multi-Attribute Vehicle Routing Problem	(Dayarian, Crainic, Gendreau, & Rei, 2015)	multi-attribute, multi depots, fleet of heterogeneous vehicles, time windows, plant requirement.
Truck and Trailer Routing Problem	(Pasha, Hoff, & Løkketangen, 2014) - (Villegas, Prins, Prodhon, Medaglia, & Velasco, 2011) - (Caramia & Guerriero, 2010a) - (Caramia & Guerriero, 2010b)-	Imcompatibilities, accessibility, fleet of heterogeneous vehicles, capacity.
Generalized Truck-and-Trailer Routing Problem	(Drexl, 2011)	single lorries and lorry-trailer combinations, Imcompatibilities, accessibility, fleet of heterogeneous vehicles, capacity, transshipment location.
Truck and Trailer Routing Problem with time Windows	(Lin, Yu, & Lu, 2011)	Imcompatibilities, accessibility, fleet of heterogeneous vehicles, capacity, time windows.
Single Truck and Trailer Routing Problem with Satelite Depots	(Belenguer et al., 2016) - (Villegas, Prins, Prodhon, Medaglia, & Velasco, 2010)	Single vehicle, facilities, main depot, accessibility, Imcompatibilities, transshipment location (satelite depot).
Multi-Period Vehicle Routing Problem - Periodic Milk Collection Problem	(Dayarian, Crainic, Gendreau, & Rei, 2015) (Claassen & Hendriks, 2007)	Multi period, fleet capacity, not compartment vehicles, fleet fixed, attention requirement, load not split, homogeneous fleet of vehicles.
Periodic Vehicle Routing Problem with time window	(Expósito, Raidl, Brito, & Moreno-Pérez, 2018)	Multi period, fleet capacity, not compartment vehicles, fleet fixed, attention requirement, load not split, homogeneous fleet of vehicles, time windows.
Multi-Period Vehicle Routing Problem with Seasonal Fluctuations	(Dayarian, Crainic, Gendreau, & Rei, 2016)	Multi period, fleet capacity, not compartment vehicles, fleet fixed, attention requirement, load not split, homogeneous fleet of vehicles, time windows., seasonality and the unpredictability supply
Dairy Transportation Problem	(Lahrichi, Crainic, Gendreau, Rei, & Rousseau, 2013)	plant requirement, collection fixed by contract (transporter), plant assigment, multi period, fleet of heterogeneous vehicles, capacity, multi depot.
Stochastic Dairy Transportation Problem	(Huang, Wu, & Ardiansyah, 2019) - (Masson, Lahrichi, & Rousseau, 2016)	plant requirement, collection fixed by contract (transporter), plant assigment, variation of demand, multi period, fleet of heterogeneous vehicles, capacity, multi depot.
Milk tanker scheduling and sequencing problem	(Basnet, Foulds, & Wilson, 1999)	Schedulling and sequencing vehicles, runs, homogeneous vehicles (tankers), assignments runs to tankers, order visit (assignment).
The Scheduling and Routing Problem	(Prasertsri & Kilmer, 2004)	sequence of pickup and/or delivery points, schedulling vehicles, capacity, time constraints, collection frequency pickup.
Symmetric Travelling Salesman Problem	(Butler, Williams, & Yarrow, 1997) - (Coltman, Schnitkey, & Miranda, 1994)	attention requirement, two-period, capacity, multi trips, fleet fixed, load not split.

Appendix C. Table of aims and model type.

Nomenclature	**Mono:** Mono-objective, **MOs:** Multi-objective			
Work or Citation	**Model type**		**Aim(s)**	**Application type**
	Mono	**Mos**		
(Montero, Canales, Paredes-Belmar, & Soto, 2019)	•		Minimize the total cost by transportation and milk demand	Real data based
(Huang, Wu, & Ardiansyah, 2019)	•		Minimize the total time for collection and delivery to the plant.	Real data based
(Expósito, Raidl, Brito, & Moreno-Pérez, 2018)	•		Minimize the lateness of the collection at each farm.	Real data based
(Caria, Todde, & Pazzona, 2018)		•	Minimize the cost of collection and CO2 emissions	Real data based
(Ghosh & Mondal, 2018)	•		Maximize the benefit of the company	Real data based
(Ruiz, 2018)		•	Minimize Total cost, time windows violations and CO2 emissions	Real data based
(O'Callaghan, O'Connor, & Goulding, 2018)	•		Minimize total distance	No application - Randomly Generated
(Paredes-Belmar, Lüer-Villagra, Marianov, Cortés, & Bronfman, 2017)	•		Maximize profit, deducting from revenue the transport, access and collection point costs	Real data based
(Mei, Jingshuai, Teng, Xiuli, & Ting, 2017)	•		Minimize total distance	Real data based
(Lou, Li, Luo, & Dai, 2016)	•		Maximize the revenue of synergies transport	No application - Randomly Generated
(Paredes-Belmar, Marianov, Bronfman, Obreque, & Lüer-Villagra, 2016)	•		Maximize profit, deducting from revenue the transportation costs	Real data based
(Masson, Lahrichi, & Rousseau, 2016)	•		Minimizes the distance covered every day to collect and deliver the milk.	Real data based
(Belenguer et al., 2016)	•		Minimize total cost for first-level trip and second-level trips	No application - Randomly Generated
(Sethanan & Pitakaso, 2016)	•		Minimizes the total costs: transportation costs and cleaning costs of the raw milk tanks on vehicles	No application - Randomly Generated
(Dayarian, Crainic, Gendreau, & Rei, 2016)	•		Minimize the transportation cost	No application - Randomly Generated
(Amiama, Pereira, Carpente, & Salgado, 2015)		•	Minimizes the total distance and total cost	Implementation in real system
(Dayarian, Crainic, Gendreau, & Rei, 2015)	•		Minimize Total Cost by routing (fixed and variable)	No application - Randomly Generated
(Dayarian, Crainic, Gendreau, & Rei, 2015)	•		Minimize the transportation cost	No application - Randomly Generated
(Drexl, 2014)		•	Minimize of a weighted linear combination of fixed vehicle costs/number of vehicles used and distance-dependent costs	No application - Randomly Generated
(Malihi & Aghdasi, 2014)	•		Maximize profit	Implementation in real system
(Mumtaz, Jalil, & Chatha, 2014)		•	Minimize facility operation costs and transportation costs (number and location of dispatch points, number of each vehicle type and vehicle routes)	No application - Randomly Generated
(Pasha, Hoff, & Løkketangen, 2014)	•		Minimize the total transportation cost	Real data based
(Lahrichi, Crainic, Gendreau, Rei, & Rousseau, 2013)	•		Minimize the transportation cost	Real data based
(Lin, Yu, & Lu, 2011)	•		Minimize total cost	No application - Randomly Generated
(Drexl, 2011)	•		Minimizes total fixed and variable costs over all lorries and all trailers	Real data based
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2011)	•		Minimize total cost	No application - Randomly Generated
(Caramia & Guerriero, 2010b)		•	Minimize the size of the fleet and the total route length	Real data based
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2010)	•		Minimize the length of first level trip and total distance by second level trips	No application - Randomly Generated
(Caramia & Guerriero, 2010a)		•	Minimize the overall number of used vehicles and total time for collection	No application - Randomly Generated
(Lin, Yu, & Chou, 2009)	•		Minimize total distance	No application - Randomly Generated
(Li, Zhang, & Jiang, 2008)		•	Minimize the total travelling distance of the trips and the gap between demand and quantity produced	Implementation in real system
(Hoff & Løkketangen, 2008)	•		Minimize the cost of all tours	Real data based
(Claassen & Hendriks, 2007)	•		Minimizes the total weighted sum of deviations on demand level	Real data based
(Scheuerer, 2006)	•		Minimize the total travel costs	No application - Randomly Generated
(Butler, Herlihy, & Keenan, 2005)	•		Minimize transport costs	Implementation in real system
(Dooley, Parker, & Blair, 2005)	•		Minimize transport costs	No application - Randomly Generated
(Prasertsri & Kilmer, 2004)		•	Minimizes the total weighted sum of total traveling distance, total time window violations, and total waiting time	Real data based
(Chao, 2002)	•		Minimize the total assignment cost	No application - Randomly Generated
(Basnet, Foulds, & Wilson, 1999)	•		Minimize make-span	Real data based
(Basnet, Foulds, & Wilson, 1997)	•		Minimize make-span	No application - Randomly Generated
(Butler, Williams, & Yarrow, 1997)	•		Minimize total distance	No application - Randomly Generated
(Coltman, Schnitkey, & Miranda, 1994)	•		Minimizes the distance covered to collect and deliver the milk.	Real data based
(Sankaran & Ubgade, 1994)	•		Minimize transport costs	Implementation in real system
(Kalra & Singh, 1988)	•		Minimize total distance	Real data based
(Cegiełła, Szymanowski, & Prokuratorski, 1986)	•		Minimize length of routes	Implementation in real system
(Harrison & Wills, 1983)	•		Minimize total distance	Real data based
(Sehulster & Pratt, 1983)	•		Minimize total distance	Real data based

Appendix D. Table of decisions addressed in studies.

Nomenclature	**Routing:** Routing Plan, **DistPlan:** Production and distribution planning, **DriSche:** Driver scheduling, **Loc:** Location - allocation collection Point or depot, **Dist or Clust:** Districting or Clustering				
Work or Citation	**Decisions**				
	Dist or Clust	**Loc**	**DistPlan**	**DriSche**	**Routing**
(Montero, Canales, Paredes-Belmar, & Soto, 2019)			●		●
(Huang, Wu, & Ardiansyah, 2019)			●	●	●
(Expósito, Raidl, Brito, & Moreno-Pérez, 2018)				●	●
(Caria, Todde, & Pazzona, 2018)					●
(Ghosh & Mondal, 2018)			●	●	●
(Ruiz, 2018)			●	●	●
(O'Callaghan, O'Connor, & Goulding, 2018)					●
(Paredes-Belmar, Lüer-Villagra, Marianov, Cortés, & Bronfman, 2017)	●	●	●		●
(Mei, Jingshuai, Teng, Xiuli, & Ting, 2017)					●
(Lou, Li, Luo, & Dai, 2016)					●
(Paredes-Belmar, Marianov, Bronfman, Obreque, & Lüer-Villagra, 2016)	●		●		●
(Masson, Lahrichi, & Rousseau, 2016)	●		●		●
(Belenguer et al., 2016)		●			●
(Sethanan & Pitakaso, 2016)			●	●	●
(Dayarian, Crainic, Gendreau, & Rei, 2016)			●		●
(Amiama, Pereira, Carpente, & Salgado, 2015)			●		●
(Dayarian, Crainic, Gendreau, & Rei, 2015)			●		●
(Dayarian, Crainic, Gendreau, & Rei, 2015)			●		●
(Drexl, 2014)		●			●
(Malihi & Aghdasi, 2014)			●		
(Mumtaz, Jalil, & Chatha, 2014)		●			●
(Pasha, Hoff, & Løkketangen, 2014)	●	●			●
(Lahrichi, Crainic, Gendreau, Rei, & Rousseau, 2013)	●		●		●
(Lin, Yu, & Lu, 2011)					●
(Drexl, 2011)		●			●
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2011)	●				●
(Caramia & Guerriero, 2010b)			●		●
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2010)		●			●
(Caramia & Guerriero, 2010a)				●	●
(Lin, Yu, & Chou, 2009)					●
(Li, Zhang, & Jiang, 2008)			●		●
(Hoff & Løkketangen, 2008)		●	●		●
(Claassen & Hendriks, 2007)	●		●		●
(Scheuerer, 2006)		●			●
(Butler, Herlihy, & Keenan, 2005)	●				●
(Dooley, Parker, & Blair, 2005)					●
(Prasertsri & Kilmer, 2004)	●				●
(Chao, 2002)					●
(Basnet, Foulds, & Wilson, 1999)				●	●
(Basnet, Foulds, & Wilson, 1997)				●	
(Butler, Williams, & Yarrow, 1997)					●
(Coltman, Schnitkey, & Miranda, 1994)			●		●
(Sankaran & Ubgade, 1994)					●
(Kalra & Singh, 1988)				●	●
(Cegiełła, Szymanowski, & Prokuratorski, 1986)					●
(Harrison & Wills, 1983)					●
(Sehulster & Pratt, 1983)					●

Appendix E. Constraints and characteristics approached in studies.

Nomenclature	**Tc/Dc:** Time or distance contraints, **TW:** Time windows, **Un/Vu:** Uncertainty and vulnerability, **St/Tt:** Service, waiting and/or travel time, **Dd:** Dead distance, **SP:** Single period, **MP:** Multi-period, **Inc:** Incompatibility, **Floh:** Homogeneous vehicles, **FloHt:** Heterogenous vehicles, **ReVeh:** Refrigerated vehicles, **Cap:** Capacity, **Env:** Environment, **Compartm:** Compartmentalized, **No Compartm:** Not compartmentalized, **ST:** Single trip, **MT:** Multi-trip, **Fix:** Fixed, **Unl:** Unlimited, **CP:** Colection points, **ReqP:** Industry or plant requeriments, **Sc:** Attention requirement of each farm, **SD:** Single depot, **MD:** Multi depot, **LoadSpl:** Splitting allowed, **LoadnSpl:** Splitting not allowed, **Acces:** Accessibility, **Preassign:** Preassignments, **Qua:** Quality, **Ccfl/Ccm:** Flow and mass conservation constraints, **Bl:** Blending, **nBl:** Not blending, **DinData:** Dinamic data, **DeteData:** Deterministic data, **StoData:** Stochastic data.				
Work or Citation	***Characteristics - Dimensions***				
	Time / Distance	**Vehicles or Fleet**	**Location**	**Product**	**Data**
(Montero, Canales, Paredes-Belmar, & Soto, 2019)	SP - Inc	FloHt - Cap - No Compartm - ST - Fix	ReqP - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Huang, Wu, & Ardiansyah, 2019)	Tc/Dc - TW - Un/Vu - St/Tt - SP - Inc	Floh - Cap - No Compartm - ST - Fix	CP - ReqP - Sc - SD - LoadnSpl	Ccfl/Ccm	StoData
(Expósito, Raidl, Brito, & Moreno-Pérez, 2018)	Tc/Dc - TW - St/Tt - MP	Floh - ReVeh - Cap - No Compartm - MT - Fix	Sc - SD - LoadnSpl		DinData - DeteData
(Caria, Todde, & Pazzona, 2018)	Tc/Dc - St/Tt - Dd - SP	Floh - ReVeh - Cap - Env - No Compartm - MT - Fix	ReqP - Sc - LoadnSpl		DeteData
(Ghosh & Mondal, 2018)	Tc/Dc - St/Tt - MP	Floh - ReVeh - Cap - No Compartm - ST - Fix	CP - ReqP - Sc - MD - LoadnSpl	Ccfl/Ccm	DeteData
(Ruiz, 2018)	Tc/Dc - TW - St/Tt - SP - Inc	FloHt - Cap - No Compartm - ST - Fix	Cp - ReqP - Sc - MD - LoadnSpl	Ccfl/Ccm	DeteData
(O'Callaghan, O'Connor, & Goulding, 2018)	MP	FloHt - RefVeh - Cap - MT	CP - Sc - SD - LoadnSpl		DeteData
(Paredes-Belmar, Lüer-Villagra, Marianov, Cortés, & Bronfman, 2017)	SP - Inc	Floh - Cap - No Compartm - ST - Fix	CP - ReqP - Sc - MD - LoadnSpl	Qua - Ccfl/Ccm - Bl	DeteData
(Mei, Jingshuai, Teng, Xiuli, & Ting, 2017)	Tc/Dc - TW - St/Tt - SP	Floh - Cap - No Compartm - ST - Fix	Sc - LoadnSpl		DeteData
(Lou, Li, Luo, & Dai, 2016)	Tc/Dc - SP	Floh - RefVeh - Cap - No Compartm - ST - Fix	SC - MD - LoadnSpl	Ccfl/Ccm	DeteData
(Paredes-Belmar, Marianov, Bronfman, Obreque, & Lüer-Villagra, 2016)	SP - Inc	FloHt - Cap - Compartm - ST - Fix	ReqP - Sc - LoadSpl - LoadnSpl	Qua - Ccfl/Ccm - Bl	DeteData
(Masson, Lahrichi, & Rousseau, 2016)	Un/Vu - MP - Inc	FloHt - Cap - No Compartm - ST - Fix	CP - ReqP - Sc - MD - LoadnSpl	Ccfl/Ccm	DeteData
(Belenguer et al., 2016)	SP - Inc	FloHt - Cap - No Compartm - MT - Fix	SC - MD - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Sethanan & Pitakaso, 2016)	Tc/Dc - St/Tt - SP - Inc	FloHt - ReVeh - Cap - Compartm - MT - Fix	CP - ReqP - Sc - MD - LoadSpl	Qua - Ccfl/Ccm - nBl	DeteData
(Dayarian, Crainic, Gendreau, & Rei, 2016)	MP - Inc	Floh - Cap - No Compartm - ST - Unl	ReqP - Sc - MD - LoadnSpl	Ccfl/Ccm	DinData - DeteData
(Amiama, Pereira, Carpente, & Salgado, 2015)	Tc/Dc - TW - MP - Inc	FloHt - RefVeh - Cap - No Compartm - MT - Fix	ReqP - Sc - LoadnSpl - Acces	Qua - nBl	DeteData
(Dayarian, Crainic, Gendreau, & Rei, 2015)	Tc/Dc - TW - SP - Inc	FloHt - Cap - No Compartm - ST - Fix	ReqP - Sc - MD - LoadnSpl		DeteData
(Dayarian, Crainic, Gendreau, & Rei, 2015)	MP - Inc	Floh - Cap - No Compartm - ST - Unl	ReqP - Sc - MD - LoadnSpl	Ccfl/Ccm	DinData - DeteData
(Drexl, 2014)	Tc/Dc - TW - St/Tt - SP - Inc	FloHt - Cap - ST - Fix	Sc - SD - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Malihi & Aghdasi, 2014)	SP		CP - Sc - MD	Qua	DeteData
(Mumtaz, Jalil, & Chatha, 2014)	Tc/Dc - SP - Inc	FloHt - RefVeh - Cap - ST - Fix	CP - Sc - MD - LoadnSpl	Ccfl/Ccm	DeteData
(Pasha, Hoff, & Løkketangen, 2014)	St/Tt - MP	FloHt - Cap - ST - Fix	ReqP - Sc - LoadnSpl - Acces		DeteData
(Lahrichi, Crainic, Gendreau, Rei, & Rousseau, 2013)	Tc/Dc - St/Tt - MP - Inc	FloHt - Cap - Compartm - ST - Fix	CP - ReqP - Sc - MD - LoadnSpl - Preassign	Qua - Ccfl/Ccm - nBl	DeteData
(Lin, Yu, & Lu, 2011)	TW - St/Tt - SP - Inc	Floh - Cap - No Compartm - ST - Fix	Sc - SD - LoadnSpl - Acces		DeteData
(Drexl, 2011)	Tc/Dc - TW - St/Tt - SP - Inc	FloHt - RefVeh - Cap - Compartm - ST - Fix	Sc - SD - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2011)	SP - Inc	FloHt - Cap - No Compartm - ST - Fix	SC - MD - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Caramia & Guerriero, 2010b)	Tc/Dc - TW - SP - Inc	FloHt - ReVeh - Cap - Compartm - ST - Fix	Sc - SD - LoadSpl - Acces	Qua - Ccfl/Ccm	DeteData
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2010)	SP	FloHt - Cap - No Compartm - MT - Fix	SC - MD - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Caramia & Guerriero, 2010a)	Tc/Dc - St/Tt - SP - Inc	FloHt - Cap - No Compartm - ST - Fix	Sc - SD - LoadnSpl - Acces	Ccfl/Ccm	DeteData
(Lin, Yu, & Chou, 2009)	SP	Floh - Cap - ST - Fix	Sc - SD - LoadnSpl - Acces		DeteData
(Li, Zhang, & Jiang, 2008)	Un/Vu - SP	Floh - Cap - ST	Sc - LoadnSpl		StoData
(Hoff & Løkketangen, 2008)	Tc/Dc - SP - Inc	FloHt - RefVeh - Cap - Compartm - MT - Fix	ReqP - Sc - MD - LoadnSpl - Acces	Qua - nBl	DeteData
(Claassen & Hendriks, 2007)	Tc/Dc - MP - Inc	FloHt - Cap - No Compartm - ST - Fix	ReqP - Sc - LoadnSpl	Qua	DeteData
(Scheuerer, 2006)	SP - Inc	Floh - Cap - No Compartm - ST - Fix	Sc - SD - LoadnSpl - Acces		DeteData
(Butler, Herlihy, & Keenan, 2005)	SP	Cap - ST	Sc - LoadnSpl	Qua	DeteData
(Dooley, Parker, & Blair, 2005)	SP - Inc	FloHt - Cap - No Compartm - MT - Fix	Sc - LoadnSpl	Qua - nBl	DeteData
(Prasertsri & Kilmer, 2004)	Tc/Dc - TW - St/Tt - SP	FloHt - Cap - ST - Fix	ReqP - Sc - LoadnSpl		DeteData
(Chao, 2002)	SP - Inc	Floh - Cap - No Compartm - Fix	Sc - LoadnSpl - Acces		DeteData
(Basnet, Foulds, & Wilson, 1999)	St/Tt - SP	Floh - Cap - MT - Fix	Sc - SD - LoadnSpl		DeteData
(Basnet, Foulds, & Wilson, 1997)	St/Tt - SP	FloHt - Cap - No Compartm - ST - Fix	Sc - LoadnSpl		DeteData
(Butler, Williams, & Yarrow, 1997)	MP	ST	Sc - SD		DeteData
(Coltman, Schnitkey, & Miranda, 1994)	MP	Floh - Cap - MT - Fix	CP - Sc - LoadnSpl		DeteData
(Sankaran & Ubgade, 1994)	Tc/Dc - SP	FloHt - Cap - No Compartm - MT - Fix	CP - Sc - LoadnSpl		DeteData
(Kalra & Singh, 1988)	Tc/Dc - MP	FloHt - Cap - No Compartm - ST - Fix	CP - Sc - MD - LoadnSpl		DeteData
(Cegiełła, Szymanowski, & Prokuratorski, 1986)	Tc/Dc - TW - SP - Inc	FloHt - RefVeh - Cap - Compartm - MT - Fix	CP - Sc - MD - LoadnSpl - Acces		DeteData
(Harrison & Wills, 1983)	SP	Floh - Cap - No Compartm - MT - Fix	CP - Sc - MD - LoadnSpl		DeteData
(Sehulster & Pratt, 1983)	SP	Floh - Cap - No Compartm - ST - Fix	Sc - MD		DeteData

Appendix F. Methodological approach and solution methods.

Nomenclature	**M.A:** Methodological Approach, **MILP:** Mixed Integer Linear Programming, **MIP:** Mixed Integer Programming, **GRASP:** Greedy randomized adaptive search procedure, **VNS:** Variable neighborhood search, **VND:** Variable neighborhood descent, **ACO:** Ant Colony Optimization, **ALNS:** Adaptive large neighborhood search, **SA: S**imulated Annealing, **GA:** Genetic Algorithm, **InfSol:** Infeasible solutions		
Work or Citation	**M.A**	**Method**	**InfSol**
(Montero, Canales, Paredes-Belmar, & Soto, 2019)	Optimization	Metaheuristic GRASP	
(Huang, Wu, & Ardiansyah, 2019)	Sthochastic Optimization	Heuristic based on set covering with saving and sweep heuristics	
(Expósito, Raidl, Brito, & Moreno-Pérez, 2018)	Optimization	Hybrid metaheuristic that combines components of GRASP and VNS	•
(Caria, Todde, & Pazzona, 2018)	Simulation & Optimization	Simulation model with an ACO algorithm embedded	
(Ghosh & Mondal, 2018)	Optimization	MILP which includes parameters related to milk collection, production of all ranges of milk-products and their distribution.	
(Ruiz, 2018)	Optimization	Clarke and Wright heuristic - Weighted sum method	
(O'Callaghan, O'Connor, & Goulding, 2018)	Simulation & Optimization	Large Neighborhood Search	
(Paredes-Belmar, Lüer-Villagra, Marianov, Cortés, & Bronfman, 2017)	Optimization	MILP and Heuristic procedure of three stages: covering problem, route generation, and route selection	•
(Mei, Jingshuai, Teng, Xiuli, & Ting, 2017)	Optimization	Improved C-W Algorithm	
(Lou, Li, Luo, & Dai, 2016)	Optimization	Two stage algorithm: first phase of dynamic programming and second stage geometry method	
(Paredes-Belmar, Marianov, Bronfman, Obreque, & Lüer-Villagra, 2016)	Optimization	MILP and Heuristic procedure of three stages: clustering, assigning milk quotas and allocating trucks to each cluster, and routing	•
(Masson, Lahrichi, & Rousseau, 2016)	Optimization	A two-stage method heuristic: Compute high-quality routes using ALNS and assignment of the routes to the plants on a daily basis.	
(Belenguer et al., 2016)	Optimization	A Branch-and-Cut Algorithm with MIP tightened with several families of valid inequalities	
(Sethanan & Pitakaso, 2016)	Optimization	Metaheuristic differential evolution (DE) algorithm	
(Dayarian, Crainic, Gendreau, & Rei, 2016)	Optimization	An adaptive large-neighborhood search heuristic	•
(Amiama, Pereira, Carpente, & Salgado, 2015)	Optimization	Spatial decision support system which two stages: First SA generating solutions, in a second step, a graphic interface, which allows interaction and changes on the routes generated.	
(Dayarian, Crainic, Gendreau, & Rei, 2015)	Optimization	A column generation approach with branch-and-price methodology	
(Dayarian, Crainic, Gendreau, & Rei, 2015)	Optimization	A branch-and-price approach with column generation, tabu search and dynamic programming for solve subproblems	
(Drexl, 2014)	Optimization	Five branch and cut algorithms	
(Malihi & Aghdasi, 2014)	Simulation & Optimization	Simulation model with a GA algorithm	
(Mumtaz, Jalil, & Chatha, 2014)	Optimization	RP Algorithm	
(Pasha, Hoff, & Løkketangen, 2014)	Optimization	Hybrid algorithm local search and tabu search: Firts stage clustering with heuristic based on local search and second stage generate a rputes and insertion of parking places	•
(Lahrichi, Crainic, Gendreau, Rei, & Rousseau, 2013)	Optimization	Unified Tabu Search Algorithm	•
(Lin, Yu, & Lu, 2011)	Optimization	Simulated Annealing Methaheuristic	
(Drexl, 2011)	Optimization	A Branch-and-Price and Heuristic Column Generation	
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2011)	Optimization	Hybrid methaheuristic based on a GRASP, variable neighborhood search and a evolutionary path relinking	•
(Caramia & Guerriero, 2010b)	Optimization	Heuristic with two mathematical formulations and local search, all embedded within a multiple-restart mechanism and tabu memory	
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2010)	Optimization	Two Metaheuristics GRASP/VND and Multi-start Evolutionary Local Search	
(Caramia & Guerriero, 2010a)	Optimization	Two Phase Heuristic	•
(Lin, Yu, & Chou, 2009)	Optimization	Simulated annealing (SA) heuristic	
(Li, Zhang, & Jiang, 2008)	Simulation & Optimization	Montecarlo simulation and the Nearest Insertion algorithm - local search heuristic for generate trips	
(Hoff & Løkketangen, 2008)	Optimization	Tabu Search Methaheuristic	•
(Claassen & Hendriks, 2007)	Optimization	MILP with Special Ordered Sets type	
(Scheuerer, 2006)	Optimization	Two construction heuristics and a tabu search heuristic	•
(Butler, Herlihy, & Keenan, 2005)	Optimization	Decision support system based on clustering algorithm and tsp algorithm	
(Dooley, Parker, & Blair, 2005)	Optimization	Evolver genetic algorithm software	
(Prasertsri & Kilmer, 2004)	Optimization	The Resource Assignment Algorithm (cluster) and The Sequence-and-Route Improvement Algorithm (routing)	
(Chao, 2002)	Optimization	A tabu search method	•
(Basnet, Foulds, & Wilson, 1999)	Optimization	Integer programming algorithm within an overall branch and bound approach	
(Basnet, Foulds, & Wilson, 1997)	Optimization	Decision support system based on heuristics - critical path based (decreasing, increasing and random allocation), greedy allocation and myopic allocation	
(Butler, Williams, & Yarrow, 1997)	Optimization	MIP with valid cutting plane inequalities and Branch-and-Bound	
(Coltman, Schnitkey, & Miranda, 1994)	Optimization	Heuristic GLM to routing and reallocating farms into loads	
(Sankaran & Ubgade, 1994)	Optimization	Decision Support System which employs heuristics	
(Kalra & Singh, 1988)	Optimization	A vehicle scheduling model	
(Cegiełła, Szymanowski, & Prokuratorski, 1986)	Optimization	A collection optimization system based on The MULTICOLMILK procedure	
(Harrison & Wills, 1983)	Optimization	Heuristic	
(Sehulster & Pratt, 1983)	Optimization	Computerized vehicle scheduling program which employs a heuristic	

Appendix G. Studies addressed districting decisions in the milk collection context.

Investigación	**Sector / Área**	**Contexto de Aplicación**	**Software**
(Paredes-Belmar et al., 2017)	Agricultural	Milk Collection	CPLEX Version 12.6 and AMPL version 20130109
(Paredes-Belmar et al., 2016)	Agricultural	Milk Collection	CPLEX Version 12.5 and AMPL version 20130109
(Masson, Lahrichi, & Rousseau, 2015	Agricultural	Annual dairy transportation problem	C++ and Cplex 12.5.0.1
(Pasha, Hoff, & Løkketangen, 2014)	Agricultural	Truck and Trailer Vehicle Routing Problem	Microsoft Visual studio 2007 using C++
(Lahrichi et al., 2013)	Agricultural	Milk Collection	C++
(Villegas et al., 2011)	Agricultural	Truck and Trailer Routing Problem	Java and Eclipse JDT 3.5.1
(Claassen & Hendriks, 2007)	Agricultural	Milk Collection	Microsoft Access and Xpress
(Butler, Herlihy, & Keenan, 2005)	Agricultural	Milk Collection	Does not specify
(Prasertsri & Kilmer, 2004)	Agricultural	Milk Collection	ArcLogistics Route (ALR)

Appendix H. Decisions approached in studies that addressed districting decisions in the milk collection context.

Nomenclature	**Routing:** Routing Plan, **DistPlan:** Production and distribution planning, **DriSche:** Driver scheduling, **Loc:** Location - allocation collection Point or depot, **Dist or Clust:** Districting or Clustering				
Work or Citation	**Decisions**				
	Dist or Clust	**Loc**	**DistPlan**	**DriSche**	**Routing**
(Paredes-Belmar, Lüer-Villagra, Marianov, Cortés, & Bronfman, 2017)	●	●	●		●
(Paredes-Belmar, Marianov, Bronfman, Obreque, & Lüer-Villagra, 2016)	●		●		●
(Masson, Lahrichi, & Rousseau, 2016)	●		●		●
(Pasha, Hoff, & Løkketangen, 2014)	●	●			●
(Lahrichi, Crainic, Gendreau, Rei, & Rousseau, 2013)	●		●		●
(Villegas, Prins, Prodhon, Medaglia, & Velasco, 2011)	●				●
(Claassen & Hendriks, 2007)	●		●		●
(Butler, Herlihy, & Keenan, 2005)	●				●
(Prasertsri & Kilmer, 2004)	●				●

Appendix I. Notation districting model with location – allocation decisions.

Sets:

N: Set of farms (basic units).

C: Set of collection center types (centers).

K: Set of candidate location of collection centers (potential location).

V: Set of vehicle types.

Parameters

I: Number of collection center to open (number of districts).

d_{ik}: Distance from farm ***i*** to candidate location ***k***.

d_{max}: Distance limit between a farm and their collection center assigned.

o_i: Daily milk supply of farm ***i***.

c_c: Cost to open the collection center type ***c***.

c_v: Operation cost vehicle ***v***.

pm: Upper bound parameter of deviation between capacity utilization of collection centers.

p: Target percentage of fleet capacity use.

cap_c: Capacity of collection center type ***c***.

cap_v: Capacity of vehicle ***v***.

m_c: Greater capacity between collection centers ***c***.

Decision variables

Y_{ck}: Binary variable equal to 1 if collection center ***c*** enters operation in candidate location ***k***.

X_{ik}: Binary variable equal to 1 if farm ***i*** is allocated to collection center in candidate location ***k***.

W_{vk}: Non-negative integer variables that define the number of vehicles type ***v*** allocated to the collection center in candidate location ***k***.

Auxiliary decision variables

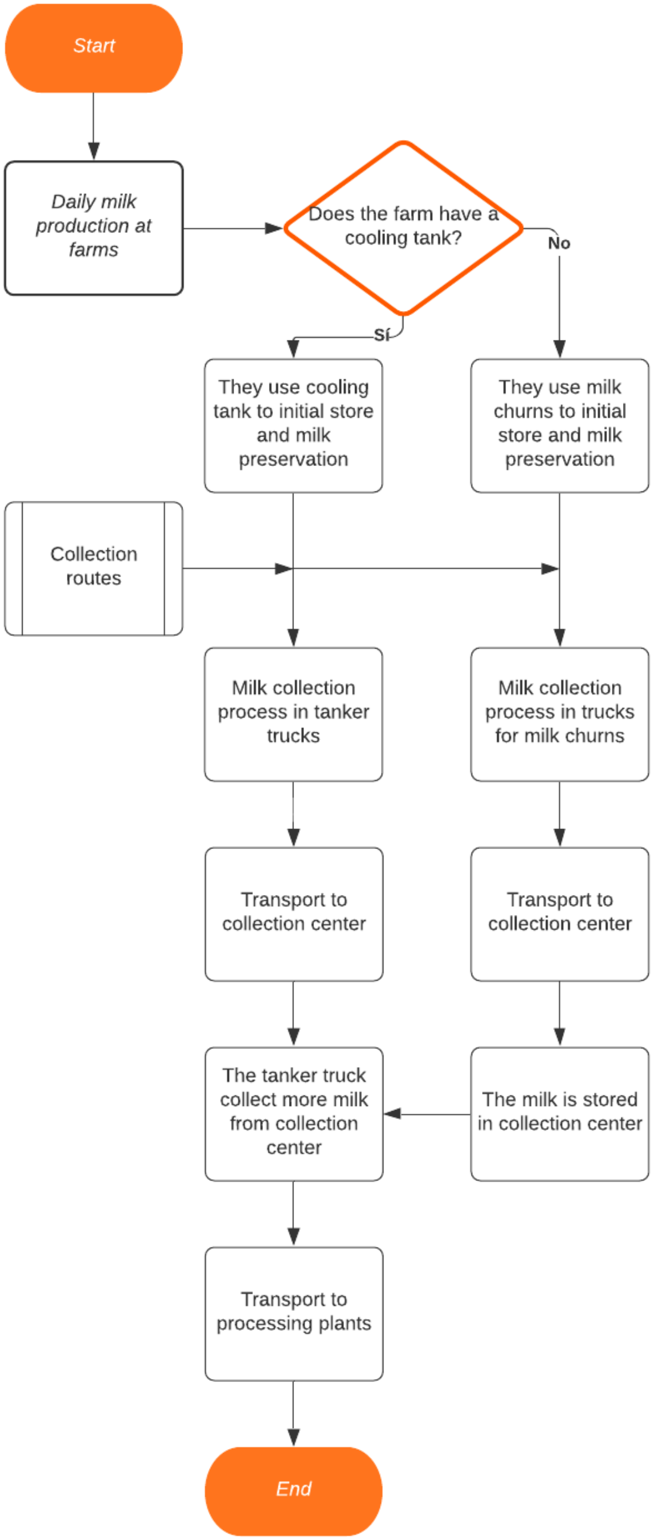
U_{ck}: Capacity utilization percentage of collection type ***c*** in candidate location ***k***.

U_k: Capacity utilization percentage of collection in candidate location ***k***.

U_{max}: Maximum capacity utilization percentage among collection centers in operation.

U_{min}: Minimum capacity utilization percentage among collection centers in operation.

Appendix J. Milk collection process flow chart.



Appendix k. Case study instance data.

https://acortar.link/hQHry6

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