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Strategic Analysis of the Dairy Transportation Problem

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Abstract. The dairy transportation problem consists of determining the best routes to be performed for collecting milk from farms and delivering to processing plants. We study the particular case of the province of Quebec, where the Fédération des producteurs de lait du Québec (FPLQ) is responsible for negotiating the transportation cost on behalf of producers. Several issues are highlighted in the actual process of designing contracts such as using historical data. We propose an approach based on scenario analysis which consists of revising both the steps and the information used to construct the routes. We develop a generalized tabu search algorithm that integrates the different characteristics of the dairy transportation problem.

Keywords: Dairy transportation problem, tabu search, scenario analysis.

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1 Introduction

In 2010, the dairy industry ranked third in the Canadian agricultural sector in terms of value [5]. About 49% of Canada's dairy farms are located in the province of Quebec, and the average milk production per farm is about 4 500 hectoliters. Three major dairy enterprises (Saputo, Agropur, and Parmalat) process 75% of the milk produced in Canada. About 50% of the dairy establishments are located in Quebec. The Canadian dairy sector is supply management based, i.e., it is based on planned domestic production, regulated prices on production, and controlled dairy-product imports. Such system applies in Canada for milk, cheese, poultry and eggs.

The movement of milk from farms to processing plants and then to consumers is centrally coordinated by government and industry partners. In Quebec, the Fédération des producteurs de lait du Québec (FPLQ), a coalition of dairy farmers founded in 1983, is responsible for managing and centrally negotiating the costs, quotas, fares, and transportation of the milk that is produced in the province. The budget of transportation is more than $70 million annually and more than 28 million kilometers are traveled. The transport of milk from farms to processing plants is fundamental in the supply chain of milk and is the focus of this study.

The problem of transporting the milk from origin to destination at a minimal cost is referred to as the dairy transportation problem (DTP). It is a complex exercise. First, the territory covered is huge: almost 600 000 sq. mi. Figure 1 illustrates the distribution of dairy farms and processing plants in Quebec.

Second, the FPLQ is responsible for negotiating, on behalf of the dairy farmers, annual transportation contracts with the transporters. The cost of transportation falls under the milk transportation agreement, which provides a rating formula. This formula is complex and nonlinear, and includes among other things the number of dairy farms to be visited in a route, the volume of milk collected, and the distance traveled. The average cost of transportation is about $2.40/hl [11]. Third, the stakeholders, especially the farmers and the transporters, have conflicting objectives; this makes the problem challenging. The regulations are strict, and various union restrictions have to be factored in the decisions made in the process of constructing the best routes. A negotiation takes place through the FPLQ to discuss and determine the cost, and contracts then formalize the agreement. In 2009, there were more than 90 contracts. Each contract with a transporter concerns multiples routes, which consists of an origin (the vehicle depot), a collection sequence (of farms), a destination (the enterprise that processes the milk), and a day of service. About 575 routes are designed each year. Good routes are essential to maintain efficient operations. The approach used by the FPLQ to construct the milk routes is mainly based on historical data. The FPLQ keeps the set of producers to be collected in each route fixed, but determines the right sequence of collecting whenever negotiations with transporters occur.

The contribution made in this paper is in the study of the decisional process associated

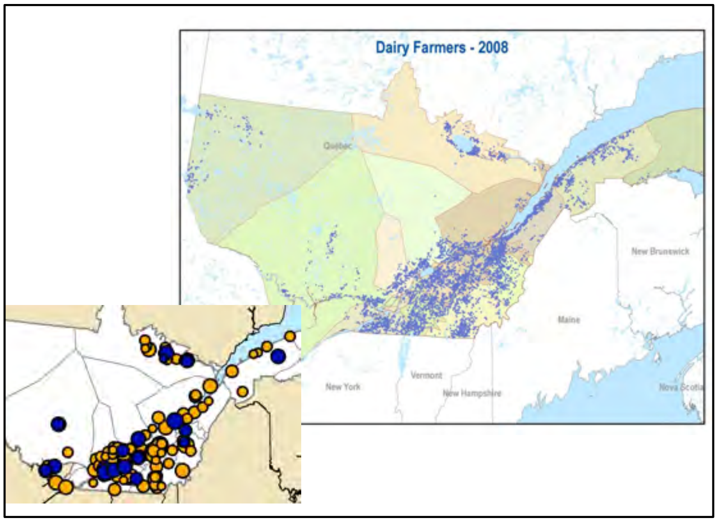

Figure 1: Distribution of supply and demand in province of Quebec.

to the dairy transportation problem considered and in the proposed strategies aimed at improving the overall solution approach that is used. Our objective is threefold. First, we study the process for designing the contracts to determine the transportation cost from an operational research point of view, in which the optimization of routes forms the basis for establishing contracts. Second, we consider the DTP as a whole and take into account the supply, demand, and transportation; existing methods in the literature do not consider all of these characteristics, and particularly the demand. Usually only one plant is considered (thus receiving the complete collection of milk). The demand in our case might come from different plants and each of them has a specific requisition with the allowed buffer in delivery. Finally, we provide a scenario analysis so that the FPLQ has information to support the cost negotiation with the transporters. The scenario analysis consists of revising both the steps and the information used to construct the routes. We analyse how the producers are assigned to transporters, how the processing plant is chosen and finally how the collection sequence is constructed. We use a metaheuristic consisting of a generalized version of unified tabu search [8] that integrates the different characteristics of the problem. More specifically, we include the delivery destination at the end of routes, different capacities for the vehicles, different number of vehicles at each depot and multiple depots and periods at the same time. This algorithm is general and flexible and can solve the vehicle routing problem with multiple characteristics.

The paper is organized as follows. Section 2 describes the DTP in detail and Section 3 presents the related literature. Section 4 presents our generalized approach and the different scenarios that we consider. Section 5 discusses our methodology, Section 6 presents the results, and Section 7 provides concluding remarks.

2 The dairy transportation problem

To present the DTP we differentiate between the *theoretical* transportation plan and the *daily* transportation plan. The theoretical plan is the basis for creating the contracts with transporters and determining the cost, while the daily plans accounts for day-to-day operations and includes any unexpected events or supply-demand adjustments.

2.1 The theoretical DTP

The aim of the theoretical plan is to establish the transportation cost to be paid by each producer as a cost per hectoliter.

Each transporter owns $\sum_o m_o$ vehicles that are not necessarily based in one depot. Because of the size of the territory, a transporter might use different depots for its vehicles. Since all the vehicles in one depot are owned by the same transporter, henceforth we will refer to depots rather than transporters. To determine the transportation cost to be paid by each producer, the FPLQ generates routes ensuring that every farm's milk is collected and all the plants receive a delivery. Figure 2 shows an illustration of a typical route. Each route consists of a depot d, a sequence of collection points $f_1, f_2, ..., f_n$, and a delivery point p. The vehicle always returns to the depot. Figure 2 shows the route of vehicle 1 originating from depot 1 for days 1 and 2.

The total cost of the route is split among the producers, and the resulting cost must be paid by each producer to his assigned transporter. To determine the routes, the FPLQ uses a process mainly based on historical data indicating the service day, the route, and the plant for each producer. This process will be presented in Section 4. Software is then used to construct the collection sequence. Thus, the theoretical DTP is in practice solved in two phases, and the first is fixed and never reconsidered. In the case of unpredicted events, the routes are adjusted. The contracts between producers and transporters cover changes related to the delivery destination (change in demand, cleaning, breakdown, etc.); these changes may require a route to be diverted to another plant. To specify the cost of the diversion, a complete list of costs is generated for each plant, with the same collection sequence. The FPLQ uses an a priori strategy rather than dynamically setting the cost. Figure 3 illustrates the process. The route presented initially delivered to plant p_1, but it has been rerouted to plant p_2 without a reoptimization of the collection sequence. Clearly the route should have been reoptimized given the new destination.

The current regulations are particularly strict and do not allow the production of different products at the same farm. Thus, only one product is available at each location, either regular, organic, kosher, etc., and each vehicle contains only one product type. The problem can therefore be solved for each product type independently.

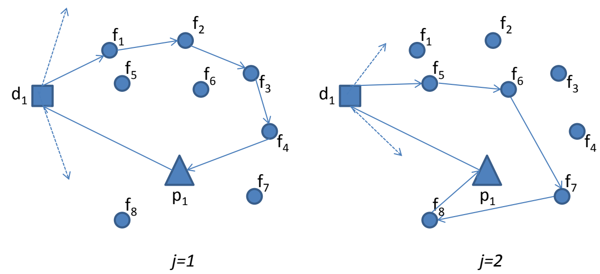

Figure 2: Illustration of possible route

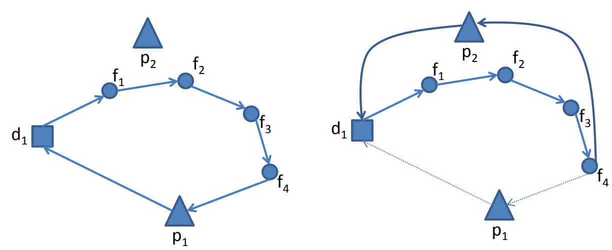

Figure 3: Illustration of diversion of route to alternative plant

The determination of an optimal theoretical plan is challenging. First, the problem is large. For example, in 2009, there were 6 452 operational farms, 90 transporters covered the territory using 265 vehicles, 90 plants transformed the milk collected, and a total of 575 routes and approximately 77 000 costs were generated [11]. Second, the problem is NP-hard and is complex to solve. Third, while constructed routes must balance the interests of the producers (who wish to minimize the transportation cost) and the transporters (who provide the service), the FPLQ is the go-between in the negotiations and needs the best informations (i.e., routes) in the negotiations rounds.

To summarize, the solution of the theoretical DTP determines 1) the routes to be performed (assignment of producers to routes (depot, vehicle, day, plant) and the sequence of visits), and 2) the transportation cost to be paid by each producer.

2.2 The daily DTP

As mentioned in the introduction, the dairy sector is supply-management based. Each producer has a quota, which implies that the monthly production is known in advance, but unexpected events (poor milk quality, breakdowns at the farm, livestock sickness, vehicle unavailability, road access, etc.) or normal variation (day-to-day variation in production) may occur.

Because of these variations, each week the FPLQ estimates the supply based on the cycle of milk production and the available quota for each producer, and matches it to the requisitions received from the plants. The milk classification system (direct consumption, used to produce cheese, etc.) is used to determine how to fulfill the demand on each day: milk for direct consumption is the priority, and the remainder is fairly distributed.

It is clear that the theoretical routes constructed to design the contracts are not followed in practice because of the variations. New routes are regularly generated. These routes are constructed to be as similar as the theoretical routes given that the transportation cost is already calculated and thus fixed by contract. The cost is adjusted whenevr there is an increase observed, otherwise the cost to be paid is that appearing in the contract. An audit process is put in place by the FPLQ to monitor the alterations to the transportation plan and to determine how the cost is billed. Such process is necessary to ensure that all involved parties are treated fairly and to control the gap between the contractual cost and that actually invoiced by the transporters.

2.3 Discussion

Every year contracts have to be negotiated between the tranporters and the FPLQ. Using the theoretical routes to determine the cost to pay, an afreement is reached by both parties. In fact, the FPLQ estimates that these theoretical routes and therefore the contractual costs, are reliable because the routes are performed in pratice in most cases. Thus, focusing on the theoretical DTP to best establish the contracts is fundamental.

To solve the DTP in practice, the FPLQ uses historical data. Each farm is historically assigned to a transporter, to a route and a service day, and finally to a processing plant. The plant assigned to each route is its "usual" plant (the plant used 75 to 80% of the time). When these assignments have been determined, the routes are constructed using an optimization tool.

Several issues arise regarding the use of historical data and hierarchical assignments when designing these contracts:

1. the territory is clustered and divided among transporters without minimizing the total transportation cost;
2. the assignment of a producer to a particular service day is not optimized;
3. producers are first clustered and then assigned to routes;
4. each route is assigned to a specific plant based on historical deliveries;
5. new farms (not in previous contracts) are simply added to the closest route;
6. when deliveries are diverted to an alternative plant, the collection sequence should be reoptimized.

We propose to address these issues simultaneously by solving the contract-design problem without relying on historical data. More formally, for the FPLQ, the problem consists in determining the minimal cost for transporting milk from farms to plants subject to constraints on the capacity of the vehicles. The solution should specify the service day for each farm, the collection sequence for each vehicle, and the plant to which each vehicle is assigned.

Formally, the DTP consists in solving a particular case of the multi-depot periodic vehicle routing problem with pick-up and delivery. In terms of both theory and application, this is a challenging problem with multiple characteristics. As highlighted in [3], the milk problem is much more complex than other collection problems, even those that concern perishable food [14, 19, 20]. We will use an approach based on scenario analysis to evaluate the impact on each of the stakeholders of changes to the process for determining the best routes.

3 Literature review

The literature on the DTP is scarce. Most papers focus on the milk supply-and-demand market [16], the delivery of finished products from plants to consumers [**?**] or a specific aspect of the problem as detailed below. The milk transportation problem is used in the literature [10, 17] to illustrate both the challenges of vehicle routing problems with multiple constraints and those of supply chain management where one aims to find the best logistic strategy. Briefly, in the solution of the theoretical DTP, complications arise from the size of the problem, the need to account for the plants and their demands, and the constraints related to the work rules agreed with the transporters.

The delivery of products from plants to clients is considered in [**?**], where a five-level hierarchical distribution structure is used to service customers. The customers are assigned to individual routes (clustering of the territory), and the problem for each vehicle reduces to a traveling salesman problem. There is a clear parallel between this approach and that currently used by the FPLQ, where the decisions (assignment of farms to routes and assignment of routes to plants) are made in advance and the only remaining problem is the sequencing of the collection. However, this approach is inadequate when a large territory and numerous plants and customers are involved. The same traveling salesman approach is used in [3].

Most research concentrates on the transportation of the milk with a focus on developing decision support systems (DSS) that include only some of the characteristics of the problem. In [4] for example, because of the complexity of the problem and the importance of social constraints that are hard to model, the DSS aims to help the scheduler rather than to replace him.

A simpler version of the DTP considers only one delivery plant. In [18], the length of the routes is the complicating constraint, and the time between pickup and delivery must not exceed a specified limit. A DSS is developed and it provides better routes. In [2], the context is rural areas where, once again, only one processing plant receives all the deliveries. A hard constraint on the number of pumps available at the plant modifies the objective of the problem. The problem is now to schedule vehicles such that on delivery they can be emptied as soon as possible. Therefore, the objective is to minimize the total operation time including idle time (while waiting to be emptied) and collection time.

In [6], the multiplicity of the products is highlighted. Thus, the routing must consider how to fill the different truck compartments. Compatibility constraints between the vehicles and the facilities at the farms also need to be considered. The objective here is to minimize the number of trucks and the tour lengths, and a local search is used to solve the problem. Another research [9] relates to the specificity of the product in New Zealand. The problem tackeld consists of on-farm milk segregation to keep milk with high value properties separate from bulk milk. Only the collecting part of the problem is analyzed and a genetic algorithm is used to determine the best collecting sequence.

The periodicity aspect of the transportation problem is addressed in [7]. One of the objectives in the goat-milk collection problem is to ensure a uniform distribution of the product even if the demand is not smooth. The practical case studied in this paper arises in the Netherlands where the milk quotation system and the cooperative associations overlook the distribution of milk. The transportation problem is modeled as a periodic vehicle routing problem and solved using a special ordered sets approach (SOS I). Another model for the milk collection problem is proposed in [15] for the Norwegian milk transportation problem. The problem is a truck and trailer routing problem (TTRP), and it is solved via tabu search.

To the best of our knowledge, only [12] have considered the DTP as defined in our project: it involves the routing of the vehicles as well as deliveries to processing plants with defined requests for milk. A two-phase approach is used to solve the problem. In phase one, the assignment of vehicles to plants is determined by a heuristic approach applied to the generalized assignment problem. The vehicles are subsequently scheduled in phase two for the collection part of the problem given the destination determined in phase one.

This literature review shows that there is a great opportunity to explore the DTP with all the constraints specific to routing as well as the demand requisitions of the processing plants. Our contribution is both regarding the methodological aspect of solving the DTP as a whole and the application to a practical case in the quebecor dairy industry.

4 Problem statement and model

As highlighted earlier, establishing the transportation contracts is crucial for the efficient management of milk transportation. These contracts specify the milk transportation cost for each producer. To generate these costs, routes are constructed to determine the collection of milk from producers and the delivery to plants. Figure 4 displays all the route types that a vehicle might perform.

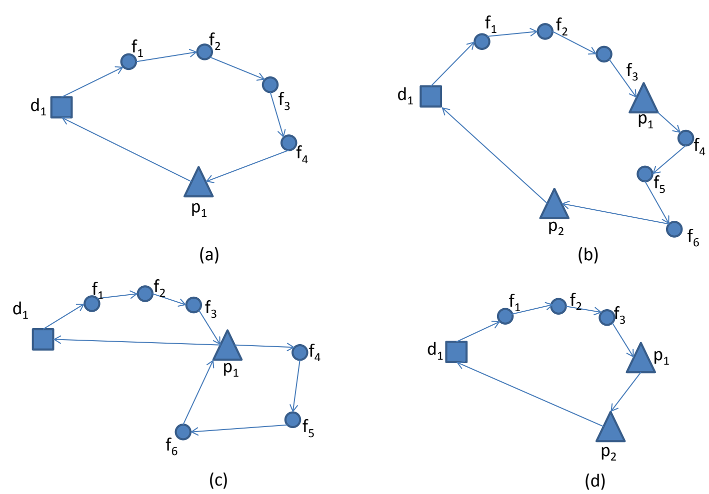

Figure 4: Illustration of all possible route types for milk collection and delivery

When a vehicle leaves the depot, it starts a collection sequence that may be interrupted by a delivery. Route (a) is the most basic: the collection sequence is completed before a delivery is made to a single plant. Route (d) is the same route but with partial deliveries, i.e., consecutive deliveries are made to two (or more) plants. This situation usually occurs when the first plant has a smaller demand. Both (b) and (c) are examples of routes with collection sequences alternating with deliveries (to the same or different plants).

Even if all these routes are performed in practice, it is important to note that only route (a) is used to generate the transportation cost. To generate the cost of routes of type (b) and (c), the route is split into two. The first route starts at the depot and returns to the depot after the first plant p_1 (thus creating an arc between p_1 and d), and the second starts at the depot and goes directly to farm f_{i+1}. The cost for routes of type (d) is generated by considering a single delivery to the more-distant plant. The total cost is then divided among the producers. Since routes of type (b), (c), and (d) are transformed into routes of type (a), we will consider only type (a) in the remainder of the paper.

The problem of determining the cost of transporting the milk from the producers to the plants may be formally represented as a heterogeneous capacitated multi-depot periodic vehicle routing problem with collection and delivery, a problem with a wide variety of constraints and characteristics. We use the notation introduced in [21] and extend the formulation of the multi-depot periodic vehicle routing problem (MDPVRP) introduced in that paper to account for the specific constraints of the DTP.

Let $G = (\mathcal{V}, \mathcal{A})$ be a graph where $\mathcal{V} = \mathcal{V}^{\mathcal{D}} \cup \mathcal{V}^{\mathcal{F}} \cup \mathcal{V}^{\mathcal{P}}$ and $\mathcal{V}^{\mathcal{D}}$ represents the set of depots, $\mathcal{V}^{\mathcal{F}}$ the set of farms, and $\mathcal{V}^{\mathcal{P}}$ the set of plants. $|\mathcal{V}| = d + n + r$, where $d = |\mathcal{V}^{\mathcal{D}}|$, $n = |\mathcal{V}^{\mathcal{F}}|$, and $r = |\mathcal{V}^{\mathcal{P}}|$. Each depot $o \in V^D$ hosts a different number of vehicles m_o. In this application, all the vehicles have two compartments. However, in the current context no mixing of products is allowed (farms produce different milk types such as regular, organic, and kosher), so the number of compartments is not a constraint in practice. The capacity of the vehicles is the only relevant characteristic. Let Q_{ko} be the physical capacity of vehicle k in depot o. Typically the vehicles are not fully utilized, and the utilization limit ρ is introduced to bound the capacity. The final vehicle-related constraint concerns the duration of the routes. Duration of routes should not exceed T hours over two days.

Each vertex $v_i \in \mathcal{V}^{\mathcal{F}}$ represents a farm requiring the collection of q_i units of milk of a defined type. Each farm requires f_i visits during the period of t days. In the general problem, each farm should specify a list L_i of possible visit combinations. Let the binary constants a_{pl} be equal to 1 if day l belongs to visit-combination p, and 0 otherwise. τ_i is the time required to collect the milk at each farm; this time is proportional to the volume of milk collected.

The vertices $\mathcal{V}^{\mathcal{P}}$ represent the plants. Each plant $i \in \mathcal{V}^{\mathcal{P}}$ has a limited capacity and specifies an estimated demand. Let Q_i and D_i be these values. Since the milk market is balanced, the demand at each plant is expressed as a percentage of the total quantity available. Each plant accepts a certain variation between the demand and the quantity received. Let δ_i^+ and δ_i^- be the acceptable surplus and shortage respectively. The value of δ_i depends on the size of plant i: the acceptable variation is smaller when the plant is small.

Arc $a_{ij} \in \mathcal{A}$ represents a direct link from vertex i to vertex j, taking into account the specifications of the road network and the following restrictions:

1. an empty vehicle leaving the depot can not travel directly to a plant ($i \in \mathcal{V}^{\mathcal{D}}$ and $j \in \mathcal{V}^{\mathcal{P}}$ then $a_{ij} \notin \mathcal{A}$);
2. a vehicle must make a delivery before returning to the depot ($i \in \mathcal{V}^{\mathcal{F}}$ and $j \in \mathcal{V}^{\mathcal{D}}$ then $a_{ij} \notin \mathcal{A}$);
3. alternation between collection and delivery is prohibited ($i \in \mathcal{V}^{\mathcal{P}}$ and $j \in \mathcal{V}^{\mathcal{F}}$ then $a_{ij} \notin \mathcal{A}$).

Arc a_{ij} is assigned a cost c_{ij} representing the cost of transportation. The set $\mathcal{A}$ takes into account that farms prefer collection early in the day (there are no additional specifications for individual farms) while plants prefer delivery later in the day. For example, no collecting is allowed after a delivery and all collections must be performed before a delivery. We use two functions to estimate the transportation cost: the total distance in kilometers, and the total traveling time using real data.

Table 1 summarizes the notation introduced.

Set of vertices	Notation	Definition
Depots	d	Set of depots
	m_o	Number of vehicles for depot $i \in \mathcal{V}^{\mathcal{D}}$
	Q_{ko}	Capacity of vehicle $k = 1, ..., m_o$ for depot $o \in \mathcal{V}^{\mathcal{D}}$ (in thousands of liters)
	ρ	Recommended utilization
	T	Maximum duration for each route
Farms	s_i	Frequency of service, $i \in \mathcal{V}^{\mathcal{F}}$
	q_i	Quantity of milk to collect at farm $i \in \mathcal{V}^{\mathcal{F}}$
	τ_i	Service time for collection at farm $i \in \mathcal{V}^{\mathcal{F}}$
	L_i	List of possible visit combinations for farm $i \in \mathcal{V}^{\mathcal{F}}$
	a_{pl}	Binary constant equal to 1 if day l belongs to visit-combination p and 0 otherwise
Plants	P	Set of plants
	Q_i	Capacity of each plant $i \in \mathcal{V}^{\mathcal{P}}$
	D_i	Demand of each plant $i \in \mathcal{V}^{\mathcal{P}}$
	δ_i	Buffer of each plant $i \in \mathcal{V}^{\mathcal{P}}$
General	c^1_{ij}	Distance for arc $(i, j) \in \mathcal{A}$
	c^2_{ij}	Traveling time for arc $(i, j) \in \mathcal{A}$
	t	Number of days

Table 1: Notation

The goal is to design a set of vehicle routes that service all the customers (farms and plants) over all periods from the most appropriate depot, such that the vehicle capacity, the route duration, and the customer demand are respected, and the total cost is minimized. We now introduce the DTP flow formulation.

Three sets of binary variables are defined:

- For every $v_i \in \mathcal{V}^{\mathcal{F}}$, $p \in L_i$, and $v_o \in \mathcal{V}^{\mathcal{D}}$, y_{ipo} equals 1 if and only if farm i is assigned to visit-combination p and depot o;
- For every $v_o \in \mathcal{V}^{\mathcal{D}}$, $k = 1 \dots m_o$, $l = 1 \dots t$ and $v_i \in \mathcal{V}^{\mathcal{F}}$, z_{iokl} equals 1 if and only if vehicle k coming from depot o on day l is assigned to processing plant i;
- For $(i,j) \in \mathcal{A}$, $k = 1 \dots m_o$, $l = 1 \dots t$, and $v_o \in \mathcal{V}^{\mathcal{D}}$, x_{ijklo} equals 1 if and only if vehicle k coming from depot o on day l visits v_j immediately after v_i.

$$\text{Minimize} \sum_{i\in\mathcal{V}}\sum_{j\in\mathcal{V}}\sum_{k=1}^{m_o}\sum_{l=1}^{t}\sum_{o\in\mathcal{V}^{\mathcal{D}}} c_{ij}x_{ijklo} \tag{1}$$

$$\text{subject to} \sum_{p\in L_i}\sum_{v_o\in\mathcal{V}^{\mathcal{D}}} y_{ipo} = 1 \qquad v_i \in \mathcal{V}^{\mathcal{F}} \tag{2}$$

$$\sum_{v_j\in\mathcal{V}}\sum_{k=1}^{m_o} x_{ijklo} - \sum_{p\in L_i} a_{pl}y_{ipo} = 0 \qquad v_i \in \mathcal{V}^{\mathcal{F}} \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ l = 1 \dots t \tag{3}$$

$$\sum_{v_j\in\mathcal{V}^{\mathcal{F}}\cup\mathcal{V}^{\mathcal{P}}} x_{ojklo} \leq 1 \qquad v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \dots m_o \ ; \ l = 1 \dots t \tag{4}$$

$$\sum_{v_j\in\mathcal{V}^{\mathcal{F}}\cup\mathcal{V}^{\mathcal{P}}} x_{ijklo} = 0 \qquad v_i \in \mathcal{V}^{\mathcal{D}} \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ v_o \neq v_i \ ; \ k = 1 \dots m \ ; \ l = 1 \dots t \tag{5}$$

$$\sum_{v_j\in\mathcal{V}} x_{jiklo} - \sum_{v_j\in\mathcal{V}} x_{ijklo} = 0 \qquad v_i \in \mathcal{V} \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \dots m \ ; \ l = 1 \dots t \tag{6}$$

$$\sum_{v_i\in\mathcal{V}^{\mathcal{D}}\cup\mathcal{V}^{\mathcal{F}}}\sum_{v_j\in\mathcal{V}} q_i x_{ijklo} \leq \rho \times Q_{ko} \qquad v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \dots m_o \ ; \ l = 1 \dots t \tag{7}$$

$$\sum_{v_i\in\mathcal{V}}\sum_{v_j\in\mathcal{V}} (c_{ij} + \tau_i)x_{ijklo} \leq T \qquad v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \dots m_o \ ; \ l = 1 \dots t \tag{8}$$

$$\sum_{v_i\in\mathcal{V}^{\mathcal{D}}\cup\mathcal{V}^{\mathcal{F}}}\sum_{k=1}^{m_d}\sum_{o\in\mathcal{V}^{\mathcal{D}}} q_i x_{ijklo} \leq Q_j \qquad v_j \in \mathcal{V}^{\mathcal{P}} \ ; \ l = 1 \dots t \tag{9}$$

$$\sum_{v_i\in\mathcal{V}^{\mathcal{D}}\cup\mathcal{V}^{\mathcal{F}}}\sum_{k=1}^{m_d}\sum_{l=1}^{t}\sum_{o\in\mathcal{V}^{\mathcal{D}}} q_i x_{ijklo} \geq D_j + \delta_j^- \qquad v_j \in \mathcal{V}^{\mathcal{P}} \tag{10}$$

$$\sum_{v_i\in\mathcal{V}^{\mathcal{D}}\cup\mathcal{V}^{\mathcal{F}}}\sum_{k=1}^{m_d}\sum_{l=1}^{t}\sum_{o\in\mathcal{V}^{\mathcal{D}}} q_i x_{ijklo} \leq D_j + \delta_j^+ \qquad v_j \in \mathcal{V}^{\mathcal{P}} \tag{11}$$

$$\sum_{v_i\in\mathcal{V}^{\mathcal{P}}} z_{iklo} \leq 1 \qquad k = 1 \dots m_o \ ; \ l = 1 \dots t \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \tag{12}$$

$$\sum_{v_i\in\mathcal{V}^{\mathcal{D}}\cup\mathcal{V}^{\mathcal{F}}} x_{ijklo} - z_{jklo} = 0 \qquad v_j \in \mathcal{V}^{\mathcal{P}} \ ; \ k = 1 \dots m \ ; \ l = 1 \dots t \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \tag{13}$$

$$\sum_{v_i \in S} \sum_{v_j \in S} x_{ijklo} \leq |S| - 1 \qquad S \in \mathcal{V}^{\mathcal{F}} \cup \mathcal{V}^{\mathcal{P}} \ ; \ |S| \geq 2 \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \ldots m_d \ ; \ l = 1 \ldots t \tag{14}$$

$$x_{ijklo} \in \{0,1\} \qquad v_i \in \mathcal{V}; \ v_j \in \mathcal{V} \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \ldots m \ ; \ l = 1 \ldots t \tag{15}$$

$$y_{ipo} \in \{0,1\} \qquad v_i \in \mathcal{V} \ ; p \in L_i \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \tag{16}$$

$$z_{iklo} \in \{0,1\} \qquad v_i \in \mathcal{V}; \ v_j \in \mathcal{V} \ ; \ v_o \in \mathcal{V}^{\mathcal{D}} \ ; \ k = 1 \ldots m \ ; \ l = 1 \ldots t \tag{17}$$

Constraints (2) ensure that each farm is assigned to exactly one depot and one visit combination. Constraints (3) guarantee that visits to farms occur only in the periods for the assigned visit combination and the assigned depot. Constraints (4) ensure that the vehicles are used only once, while constraints (5) enforce compatibility issues between the route start and end points. Flow conservation constraints are imposed by (6), and the capacity of the vehicles and the duration of the routes are limited by (7) and (8). Constraints (9) ensure that the capacity of the plants is respected, while contraints (10) and (11) ensure that each plant receives its demand given the specified tolerances. Constraints (12) ensure that each vehicle is assigned to at most one plant, and constraints (13) specify these assignments. Finally, subtours are eliminated through (14). Since this problem is NP-hard, we propose a heuristic solution method, which will be described in the next section.

5 Methodology

Although the dairy industry is highly constrained given its coalitions and regulations, the determination of the optimal transportation plan will benefit both the producers and the transporters. To provide the FPLQ with the best methodology for designing routes, we used a scenario-analysis methodology. This methodology involves revising both the steps and the information used to construct the routes. Specifically, we analyze 1) how the producers are assigned to transporters (or depots) and then to routes, 2) how the service day is fixed for each farm, 3) how the processing plant is chosen, and finally 4) how the collection sequence is constructed.

5.1 Scenario definition

Assignment of farms to transporters The territory of the province of Quebec is divided among the transporters, and each covers all the farms in the assigned area. This clustering is not an annual exercise and is not redone during the negotiations, but we believe that finding the optimal clustering is essential. The first element to analyze is the assignment of farms to transporters, and the second is the assignment of farms to depots and routes. Each transporter covers a large area and owns multiple depots. Assigning a farm to the right depot and the right route is a complex exercise: in practice, more than 500 routes are generated. Choosing the best carrier, depot, and route rather than the "usual" one for each farm is the core of this scenario. This analysis will simultaneously address the fifth issue highlighted in Section 2.3, i.e., the process for including new farms and removing existing ones. This scenario assumes that both farms and transporters are independent of the territory. The optimization of the transportation cost is based only on cost reduction. Thus, farms can easily be added or removed.

Day of service Historically, milk is collected every second day at each farm. Milk is produced every day, and it should be stored at the farm for at most two days. Therefore, the farms are divided into those to be collected on day one and those to be collected on day two. The service day is determined a priori and based on the historical assignment. We propose to relax this and to determine the best service day while optimizing the routing cost.

Assignment to processing plant Before the routing of each vehicle, the "usual" plant is determined. This plant is considered to be theoretically the best assignment if 75% (or more) of the deliveries of this vehicle are directed to it. The plant is the last stop on each route and should be chosen by considering its demand and the vehicle's volume. We propose to analyze the assignment of routes to plants by simultaneously considering all the vehicles and the demand of each plant.

Routing of vehicles The final step is to route the vehicles when the day, the set of farms, and the destination are known. This is a narrowly defined exercise when all the decisions have been made earlier in the process. We aim to evaluate the impact of modifications to each of the previous decisions on the design of the routes and the total cost. The second issue, as highlighted in Section 2.3, concerns the daily operations when a vehicle is routed to a plant other than the usual one. The collection sequence is never reoptimized for different destinations. To capture this variability, we should design the routes according to all the potential delivery points. Therefore, we will analyze the effect on the costs and routes when vehicles have to change their delivery destinations.

5.2 Solution method

The DTP is solved as a special case of a heterogeneous MDPVRP with capacity and duration constraints and delivery destinations, using a modified version of the unified tabu search (UTS) algorithm [8]. It is one of the most efficient and flexible algorithms in the literature for solving both the MDVRP and the PVRP. It allows for time windows and can include the features of the DTP. See [8] for details of UTS; a brief description is presented in algorithm 1. The algorithm is based on tabu search, a metaheuristic that explores the solution space of a problem by iteratively moving from the current solution s to $s' \in N(s)$, where $N(s)$ is the neighborhood of solution s. The local search continues until the stopping criterion is satisfied.

One of the important features of UTS is that it can explore infeasible solutions, i.e., even solutions that violate the duration and capacity constraints are considered. The objective function includes dynamically adjusted penalty parameters that can encourage searching in an infeasible subspace or alternatively restore the capacity and duration constraints. The search is continuously diversified to better explore the solution space by including a penalizing factor (proportional to the frequency of the attributes of a solution) and a scaling factor (which accounts for the total solution cost and the size of the problem). In this case, an attribute is defined to be the pair (i, k) where customer i is assigned to vehicle k. A movement thus consists of replacing this pair by (i, k'), where customer i is transfered to another route k' in either the same or a different visit combination. A tabu list ensures that cycling back to the previous attribute (i, k) is forbidden for θ iterations, this value being set at the beginning of the algorithm as a function of the size of the problem. On the other hand, the aspiration criterion ensures that better solutions that contain a tabu attribute will not be missed; in this situation, the tabu status is revoked.

Algorithm 1 Outline of Unified Tabu Search Algorithm

To construct an initial solution
1) Randomly assign a visit combination (or depot) to customer i.
2) For each day (or depot) $l = 1 \ldots t$, randomly choose a customer j among those closest to the depot.
3) Start with the first route $k = 1$ and use the customer sequence $j, j+1, \ldots, n, 1, \ldots, j-1$, where n is the number of customers.
For every customer i scheduled to receive a visit on day l, if inserting customer i into route k violates the capacity or duration constraints, go to the following vehicle unless $k = m$; otherwise insert i using the GENI heuristic [13]. This insertion procedures allows to insert a customer between any given pair of customers.
while maximum number of iterations not reached **do**
  1) For each customer i, for each vehicle k, for each day (or depot) l: remove i from route k on day (or at depot) l and either insert into route k' or change visit combination with best assignment to a vehicle.
  2) Implement best non-tabu movement unless aspiration criterion is met.
  3) Adjust penalty parameters to allow for basic diversification.
  4) Update the tabu list, the frequency of the attributes, and the best-movement list.
end while

As mentioned earlier, this algorithm is designed to solve the PVRP and the MDVRP, and it can handle time windows. To adapt this algorithm to the DTP, we have included:

- multiple depots and periods;
- a variable number of vehicles at each depot;

- two types of vehicles; and
- delivery destinations at the end of the routes.

Changes to the implementation of the algorithm and the addition of one movement are needed to allow for multiple depots, multiple periods, and the heterogeneity of the vehicles. If we consider either multiple depots or multiple periods but not both, only one movement that modifies the depot assignment (or visit-combination assignment) is needed. However, in the current situation we need both multiple depots and multiple periods. For each depot, we add the flexibility of variable number of vehicles available and the capacity of each.

To address the destination issue, we add one step to the algorithm. The algorithm can be stated as follows. First, for each vehicle assign a plant for the delivery; the number of possible combinations is relatively small. In fact, plants usually receive a specific number of deliveries, and do not allow split deliveries. It is thus possible to enumerate the potential combinations of assignments of vehicles to plants. We do not implement a heuristic to determine the best assignment to a plant mainly because this assignment is not related to the relative distance to a plant or the volume. The milk travels from east to west, so all deliveries are made to the west. Finally, the objective function is modified to consider demand violation for each plant. This generalized version of UTS is called generalized unified tabu search (GUTS).

This general algorithm is sufficiently flexible for all the proposed scenarios, solving both the TSP and the DTP. It is used directly for the latter, but some steps are skipped for the former. The details are as follows:

- If the assignments are fixed, and the problem is to solve the TSP, we use GENIUS [13] to determine the sequence of the route;
- If the farms have a fixed assignment to plants, farms can not move between vehicles unless the destination is unchanged;
- If the vehicles have a fixed assignment to plants, the first phase of assigning the vehicles is skipped;
- If no assignment is fixed, GUTS is used as described.

6 Experimentation

The experimentation is based on two real-data instances of different sizes. Table 2 gives the parameters for each instance.

Each farm has a volume q_i to be collected, and the total volume is the total supply on the market. The capacity of the plants is not specified because $\forall i \in \mathcal{V}^{\mathcal{F}}, D_i + \delta_i^+ < Q_i$. Since collection typically occurs every two days, the data on the volumes to be collected

	$Inst_1$	$Inst_2$
n	73	226
d	1	4
m_i	[3]	$[1, 1, 5, 1]$
Q_{ij}	$[31, 35, 35]$	$[31; 35; 35, 35, 35, 35, 35; 35]$
p	1	3
D_i	$[5\%, 10\%, 85\%]$	$[5\%, 10\%, 85\%]$
δ_i	$[16\%, 20\%, 2\%]$	$[16\%, 20\%, 2\%]$
t	2	2
O	184 992	493 875

Table 2: Instances obtained from FPLQ for two different transporters

and the plant demands are given for these two days. All collection points have a frequency of service equal to one. Limits are specified on the demand and capacity but not the deliveries. For the first transporter $Inst_1$, only one depot hosts all three vehicles, while for the second $Inst_2$ four different depots host eight vehicles.

The experimentation is as follows. We compare the results of each of the chosen scenarios with the current routes. The scenarios question each of the decisions made: which depot to assign to farms, which vehicle to assign to farms, which service day to assign to farms, how to design the set of farms and their sequence in each route, and finally which plant to assign to a route. To compare the solutions, we proceed as follows:

- For the transporters and depots, we evaluate the composition of the routes: length, utilization of vehicles, and cost (total distance or total duration). These indicators are also classified by depot to indicate how each transporter is affected by changes to the routes.

- For the farms, we compare the service-day assignment and the assignment to the depot.

- For the plants, we evaluate the volume received versus the demand.

Table 3 gives the $Inst_1$ and $Inst_2$ solutions currently implemented at the FPLQ. The solution of $Inst_2$ has the special feature that it does not use the vehicle in depot 1 every day. In both solutions the vehicle utilization is almost always less than 97%. In practice, the utilization in $Inst_1$ of vehicle 2 on day 1 is 97.55%, which violates the capacity constraint. The average utilization is 95%. All vehicles in $Inst_1$ have the only plant 1 as a destination, while in $Inst_2$, plant 1 receives 1 delivery, plant 2 receives 2 deliveries and plant 3 the remaining deliveries. Total travel distance is 401 km in $Inst_1$ (or 234 minutes if we use the estimated travel time) and 4 761 km in $Inst_2$.

Instance	Depot	Vehicle	Day	Length of route	Volume (l)	ρ (%)	Distance (km)	Traveling time (min)	Plant
$Inst_1$	1	1	1	10	21765	62.2	65	39	1
			2	10	28416	81.2	64.8	37.3	1
		2	1	9	34141	97.6	69.8	39.1	1
			2	14	33554	95.9	70	41.5	1
		3	1	16	33832	96.7	66.6	39.4	1
			2	14	33284	95.1	65.1	38.3	1
	Total			73	**184 992**		**401.2**	**234.4**	
$Inst_2$	1	1	1	16	29791	96.10	158.6	115	1
	2	1	1	11	33808	96.59	507	296.5	3
			2	16	33747	96.42	385.2	229	3
	3	1	1	11	33364	95.33	333.4	182	2
			2	15	28720	92.65	331.3	208	3
		2	1	9	33240	94.97	234.6	141	3
			2	20	33341	95.26	337.4	220	3
		3	1	14	33264	95.04	373.2	207	3
			2	15	33302	95.15	248.5	156	3
		4	1	17	33403	95.44	246.1	147	3
			2	18	33356	95.30	251.3	155.5	3
		5	1	15	33693	96.27	244.8	151	2
			2	20	33774	96.50	260.4	194.5	3
	4	1	1	13	33879	96.80	446.7	259	3
			2	16	33193	94.84	402.8	236.5	3
	Total			226	**493 875**		**4761.3**	**2898**	

Table 3: Detailed solutions for $Inst_1$ and $Inst_2$

6.1 Collection sequence

In this first scenario, we aim to determine whether or not, with all decisions fixed, the collection sequence is optimal. The construction of the route when the depot, the vehicle, the day, the plant, and the set of farms are fixed is modeled as the traveling salesman problem. We used the GENIUS algorithm to solve this problem.

Instance	Scenario	Distance (km)	Traveling time (min)
	FPLQ	401.2	234.4
$Inst_1$	Scenario TSP	400	233.5
	Improvement in %	-0.30%	-0.38%
	FPLQ	4761.3	2898
$Inst_2$	Scenario TSP	4733.6	2868
	Improvement in %	-0.58%	-1.04%

Table 4: Optimization of collection sequence

Table 4 shows that very small improvements (less than 0.5%) can be made in all cases, even when the assignments are not modified. All the elements of the routes are fixed except the collection sequence. We present only the total distance and time since no changes were made.

6.2 Milk to Plants

Scenario $M2P$ ensures that all plants receive the same amount of milk from the same farms as in the FPLQ solution. This scenario is particularly relevant when the milk has specific properties or the plant prefers specific farms. Therefore, the problem is to determine for each (farm, plant) pair the assignment to depots, vehicles, and days. Since the set of farms is clustered, i.e., only those with deliveries to the same plant can be collected by the same vehicle, we modify the cost structure.

To make the best use of the algorithm, we modified the cost structure of the arcs: the distances (and travel times) between producers in different clusters are increased to infinity. Therefore, the problem can be modeled as an MDPVRP. Since $d = 1$ for $Inst_1$, the problem reduces to the PVRP, which can also be handled by the algorithm.

Table 5 gives the results for these instances. The capacity of the vehicle is Q_{ij} for vehicle i in depot j, but the utilization of the vehicles is restricted to 97% of the total capacity.

The results show that simply by redistributing the farms among the vehicles available at the same depot, we can reduce the cost of collecting and delivering milk. In terms of the distance traveled in kilometers, the improvement is over 2% which represents a few hundred thousand dollars of savings.

Instance	Scenario	Distance (km)	Traveling time (min)
	FPLQ	401.2	234.4
$Inst_1$	Scenario $M2P$	398.3	231.6
	Improvement in %	-0.71%	-0.96%
	FPLQ	4761.3	2898
$Inst_2$	Scenario $M2P$	4663.2	2846.5
	Improvement in %	-2.06%	-1.78%

Table 5: Cost of reassigning farms/plants to vehicles

The results in Table 5 show that the vehicle utilization is always less than 97%, which is another positive feature of this solution.

		$Inst_2, km$			$Inst_2, min$		
Stakeholder		Number of customers	Volume collected	Traveling cost	Number of customers	Volume collected	Traveling cost
Depot	1	—	—	-0.5	—	—	-1
	2	-1	+133	-83.7	+6	-64	-36.5
	3	—	-494	-37	-6	+1503	-1.5
	4	+1	+361	+23.1	—	-1439	-12.5
Plant	1		—			—	
	2		—			—	
	3		—			—	

Table 6: Variation (in units) for the different stakeholders for $M2P$

Even if all depots and vehicles in each instance are own by the same transporter, we extend the analysis to the case where the depots are owned by different transporters. From the transporter's point of view, Table 6 shows that the composition of the routes is almost identical. The indicators used to evaluate the solutions are per depot: number of customers, total volume collected, distance traveled, and travel time. For example depot 1 serves the exact same number of customers with the exact same volume to collect but with a reduced distance of 0.5 km or 1 minutes. Depot 2 serves one less customer but collects 133 hectoliters more milk. The total distance is also reduce by 83.7 km and so on. All variations of volume are in the bracket $[-2.15\%, +0.54\%]$. As required, each plant receives exactly the same volume as in the FPLQ solution.

6.3 Vehicles to plants

This scenario specifies that the transporters (vehicles) are assigned to specific plants. When we build the contracts, the vehicles are already assigned to their usual plants, and the set of farms is fixed. We propose in this scenario to determine the best set of farms to collect given that each vehicle has a preferred delivery destination. The problem involves solving an MDPVRP where each vehicle in each depot is already assigned a destination. We use GUTS to solve $Inst_2$. This scenario analysis is not relevant for $Inst_1$ since only one plant is considered.

Instance	Scenario	Distance (km)	Traveling time (min)
	FPLQ	4761.3	2898
$Inst_2$	Scenario $V2P$	4596.5	2805.5
	Improvement in %	-3.46%	-3.19%

Table 7: Cost of reassigning farms to pair of vehicles/plants

Table 7 shows that this scenario introduces greater savings. It provides greater flexibility in the assignment of farms to vehicles (and depots). If all the depots belong to the same transporter, it should be possible to implement this solution without any further negotiation for a gain of 3.46% in terms of distance or 3.19% in terms of total duration. Table 8 shows that the indicators for each stakegolder are stable. Each depot notes a decrease in terms of traveling cost (either minutes or kilometers) and a reverse relation between the increase of number of stops (producers collected) and volume. All variations of volume are in the bracket $[-1.45\%, +0.70\%]$. The service-day for each farm is difficult to analyze as each farm can be easily switched from one day to another. The number of producers per day is very comparable (120 and 106 in the FPLQ solution and 119 and 107 in $V2P$). Finally, for the plants, the service day is equivalent and the gap between the demand and the volume received is also very small and within the limits provided by the FPLQ. To decrease the cost one can observe that plant 2 receives about 2.65 and 2.74% more milk than expected when comparing to the FPLQ solution.

		$Inst_2, km$			$Inst_2, min$		
Stakeholder		Number of customers	Volume collected	Traveling cost	Number of customers	Volume collected	Traveling cost
Depot	1	-1	+216	-13.4	-1	+180	-25
	2	+5	-393	-120.7	+5	-215	-33
	3	-7	+493	-9.4	-5	+1008	-28
	4	+3	-316	-21.2	+1	-973	-8
Plant	1		+216			+180	
	2		-1747			-1689	
	3		+1531			+1509	

Table 8: Variation (in units) for the different stakeholders for $V2P$

6.4 DTP

In this scenario, we do not use any historical information to construct the routes; this is the most flexible scenario. This problem involves solving the MDPVRP and simultaneously determining which plant to assign to each route. This scenario involves solving the DTP with no a priori decisions. Table 9 shows the results.

Instance	Scenario	Distance (km)	Traveling time (min)
	FPLQ	4761.3	2898
$Inst_2$	Scenario DTP	4573	2794
	Improvement in %	-3.95%	-3.59%

Table 9: Cost of solving the DTP

The improvement is clearly superior to that for all the previous scenarios, which relax one decision at a time. From the point of view of the transporters, there are again two cases to consider. If all the depots belong to the same transporter, then the FPLQ should be able to directly implement the solution. Otherwise, it will have to negotiate the territory changes with the transporters. The following analysis shows how each stakeholder is affected by these changes.

		$Inst_2, km$			$Inst_2, min$		
Stakeholder		Number of customers	Volume collected	Traveling cost	Number of customers	Volume collected	Traveling cost
Depot	1	-2	-240	-14	-2	-2571	-24.5
	2	+3	+70	-132.7	+1	-399	-42
	3	-3	+505	-58.4	—	+3278	-28
	4	+2	-335	+16.8	+1	-308	-9.5
Plant	1		-240			-2571	
	2		+178			+633	
	3		+62			+1938	

Table 10: Variation (in units) for the different stakeholders for DTP

Table 10 shows that for all depots, variations of volume are small but for the first plant. It receives less than its demand (-8.63%) in instance $Inst_2, min$, and the surplus for the other plants ranges from 0% to 3%. This scenario shows thet greatest changes in terms of volume collected by depots and deliveries to plants. Finally, when evaluating the service day assignment, plants in both $Inst_2, km$ and $Inst_2, min$ have same day of service, but it is once again very difficult to evaluate the change in service-day assignment for the producers.

7 Conclusion

In this paper we have investigated a practical DTP in the province of Quebec. A dedicated federation negotiates the transportation plan as well as the transportation cost to be paid to the transporters. To solve this problem in a highly constrained environment (regulations and unions), the FPLQ usually uses the previous assignments to transporters, days, plants, and farms to determine each year how the milk will be routed. Each route specifies the depot, the vehicle, the day, the set of farms, the order in which the collection should be performed, and the processing plant. Using the historical data results in the fixing of all the assignments; only the optimization of the collection sequence is performed each year.

We have relaxed each of these assignments and analyzed the impact on the transportation cost. Each change has an impact on the transporters, the farms, and the plants. We have determined whether each transporter is assigned the right set of farms, whether each farm is assigned the right service day, and whether the farms are on the right routes. The results show that small improvements may be achieved by simply changing the routing of the vehicles which has the smaller impact on all stakeholders. To summarize, the improvements range from 0.5% to approximately 4% in terms of distance. In the later case, where improvements are more important, stakeholders note higher changes, which will probably require more negotiations.

Solving the theoretical DTP is essential to determine the transportation costs for the contracts. In this paper we analyze the DTP for one transporter at a time, but show the potential impact if all transporters in the territory are considered simultaneously. An interesting area for future research would be to analyze how the routes are modified if all contracts are negotiated at the same time.

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