

# Arbeidsnotat

## Working Paper

2008:6

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collection in Western Norway  
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MØREFORSKING  
MOLDE

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Arbeidsnotat / Working Paper 2008:6  
Høgskolen i Molde / Molde University College

Molde, mars / March 2008

ISSN 1501-4592

ISBN 978-82-7962-095-2 (trykt)

ISBN 978-82-7962-231-4 (elektronisk)

# A TABU SEARCH APPROACH FOR MILK COLLECTION IN WESTERN NORWAY USING TRUCKS AND TRAILERS

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## Abstract

This paper considers a real world problem for a Norwegian dairy company collecting raw milk from farmers. The problem can be classified as a special type of the *Truck and Trailer Routing Problem* which is a variant of the traditional *Vehicle Routing Problem*. The company uses a fleet of heterogeneous trucks with tanks for the milk, and a truck can either drive the route by itself or carry a trailer with an additional tank. Most Norwegian farms are small and inaccessible for vehicles with trailers, so the routes that are served with a trailer have to be constructed so that the vehicles carry the trailer to a parking place and leave it there. The truck will then drive a subtour to the farmers and collect milk before it returns to the parked trailer. It can then fill the milk over from the truck tank to the trailer tank and start on a new subtour from the same spot, or it can drive the trailer to a new parking place, fill the milk over and start a subtour from there. The milk can be stored up to three days at the farms, and in this paper we will compare different frequencies of collection, different sizes of the vehicles and the benefit of using trailers compared to driving with single trucks. We will use the tabu search metaheuristic to construct the routes for the different strategies of milk collection.

**Keywords:** *Vehicle Routing Problem, Tabu Search, Milk Collection, Truck and Trailer Routing*

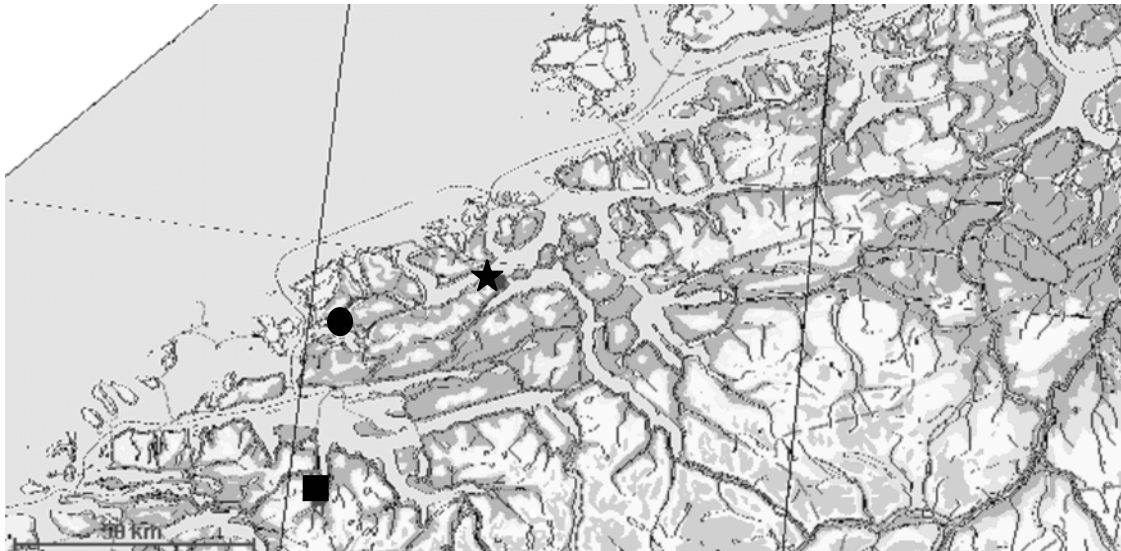
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## 1. Introduction

Milk collection is a problem which is well known in rural areas all around the world. Sankaran and Ubgade (1994) describes milk collection in Uttar Pradesh, India, where the farmers don't have cooler tanks for the milk themselves, but typically a village will have one common milk collection centre (MCC) for the farmers in the vicinity. Here the farmers have the responsibility to bring the milk to the MCC, and the dairy company will have a traditional Vehicle Routing Problem to route the collecting vehicles between the MCC's. For solving this problem they present a decision support system and show the benefits when implementing this system at the dairy company. Other decision support systems specialized for the milk collection problem exist, and Basnet and Foulds (2005) present a case study for a computer based system for routing milk tankers in New Zealand. The structure of the problem does however vary in different parts of the world, e.g. because of geographical conditions and size of the farms.

TINE BA is the leading dairy company in Norway, co-operatively owned by about 18000 milk producers all over the country. The company consists of several partly and wholly-owned subsidiaries, but the core business is producing dairy products like consumer milk, cream, butter, cheese and yoghurt from raw milk. The company is divided in five regions for the different parts of Norway, and each region consists of several dairy plants that each has a number of suppliers attached to them. In this paper we will focus on three dairy plants in the northern part of Møre & Romsdal county and the 990 suppliers attached to these plants. Figure 1 shows a map of the district, with the geographic location of the plants marked.



*Figure 1. The northern part of Møre and Romsdal County with the dairy plants marked*

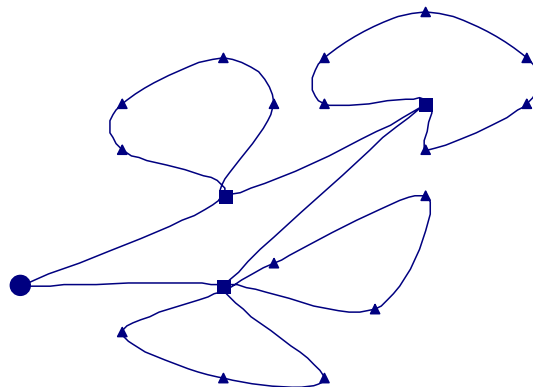
The circle indicates the position of the plant in Elnesvågen which the largest one with a demand of 77.2% of the total delivery. The star marks the position of the plant at Høgset with 17.4% of the total, and the square is the smallest plant at Tresfjord which is a special factory for two kinds of cheese, and demands 5.4% of the total. The suppliers are spread all over the county and each has a certain amount of production each day. The production will have some daily variations and the planning is done with the computed average production. With respect to the variations the plans should, however, be made with some free space in the vehicle tanks.

Each plant has an associated number of heterogeneous vehicles with or without trailers to collect the milk from the suppliers attached to that plant. The vehicles have a certain capacity which is the same number both in volume (litres) and weight (kg). Since milk has a density of 1.03, the plans have to be made according to the weight rather than the volume. The truck tanks can hold the milk from the different suppliers separate. This separation is important in cases where some herds have been treated by antibiotics because of disease. Some producers use ecological principles in their production, which means for example that they don't use chemical fertilizers. Ecological products are treated and sold separate from traditional dairy products, and another advantage of the separation in the tanks is that the same vehicle can collect both from traditional and ecological producers of milk. Some of the vehicles will in addition to the milk collection distribute whey for pig's food to the same farmers. The whey distribution is done on separate trips, however, and will not be discussed in this paper.

When the cows are milked at the farms, the raw milk is stored in a cooler tank waiting for the visit of the vehicle. Each farmer has a cooler tank with a size that is adjusted to the expected daily production and the frequency of the collecting tours. The frequency is not standardized, and different frequencies are used for different tours in the district. This difference is mainly due to historical traditions. The milk can be stored for at most three days in the cooler tank before it has to be collected, and three different frequencies are used by the company. The routes with frequency code "7x3" will be driven every third day no matter if the day is a holyday, and similarly the routes with frequency code "7x2" will be driven every second day. The third used strategy has frequency code "6x2" which means that the routes will be driven every second day but not on Sundays. Suppliers on these latter routes will then be visited at the same days every week; Monday, Wednesday, Friday or Tuesday, Thursday, Saturday. On these routes the amount to be collected will be larger on Mondays and Tuesdays because it will correspond to three days production as opposed to only two days production for the other collecting days. The size of the cooler tanks for suppliers on these routes will then have to be adjusted to the three days production interval, and a change of the tour frequency to "7x3" will thus not require any change of the size. By changing the frequency of the routes from "7x2" to "7x3" however, the cooler tanks of the suppliers will be too small, and an investment is needed to get cooler tanks of the right size. The "6x2" routes will clearly not be very efficient because they have to be planned with a three day production interval, but will be driven with less load on the truck on two of the three tours each week. Other factors like the working and spare time of the driver

and the advantage of collecting on the same weekdays may however be the advantages of such a solution.

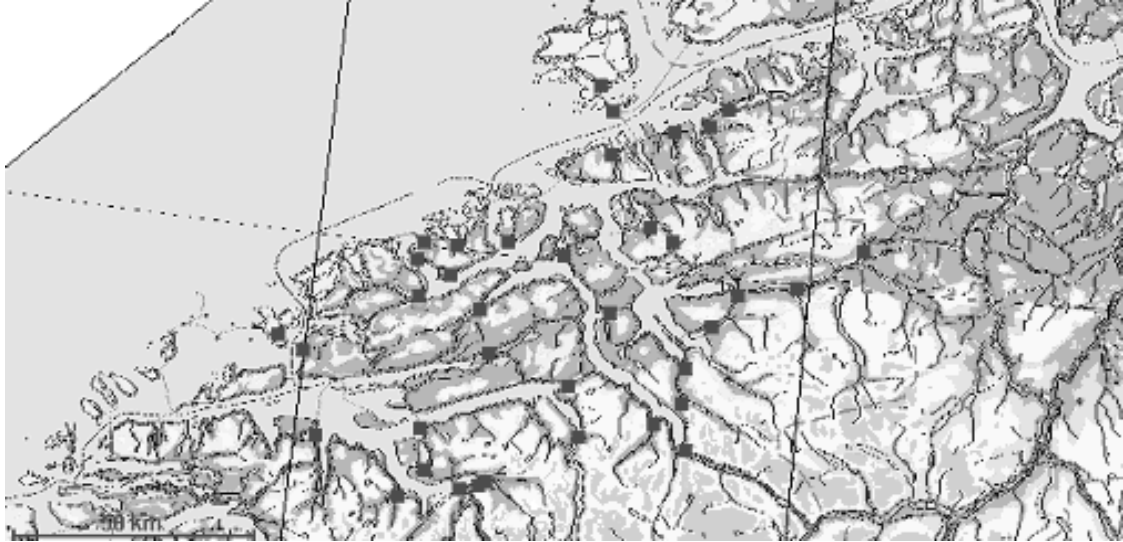
The existing routes for the dairy plants concerned are of different design according to the type of vehicle that serves them. Some routes consist of a single truck which drives to the suppliers and collects the milk. When the tour is completed, the truck will return to the depot and empty the tank, and if there is time, it will start on a new tour afterwards on the same day. For the tours that serve the suppliers far from the depot, the distance back to the depot will however be too large to make a new subtour possible. On these tours there is often a need for more tank capacity and the vehicles will typically carry a trailer to be able to collect milk from more suppliers on the same tour. Most Norwegian farms are however small and often inaccessible for a large truck with a trailer. The routes are then designed in a way that allows the trailer to be parked at a parking place while the truck is visiting the farms and collecting the milk. When the tank on the truck is full, the truck will return to the parked trailer. It can then fill the milk over from the truck tank to the trailer tank and start on a new subtour from the same spot, or it can drive the trailer to a new parking place, fill the milk over and start a subtour from there.



**Figure 2.** *The structure of solutions for milk collection used by TINE BA*

Figure 2 shows a graph which represents a solution to the milk collection problem with the constraints mentioned. The circle marks the depot, while the squares are the parking places which are used as roots for the subtours that visits the suppliers marked with triangles.

The possible parking places are prearranged mostly at large parking lots or petrol stations. TINE BA usually pays a fee to the property owner for maintenance for snow clearance etc. Figure 3 shows the same map as Figure 1 with all the possible parking places used by TINE BA marked with squares. This type of solutions, with the trailer serving as a mobile depot for the truck, was first described by Vahrenkamp (1989) for the milk collection in Western Germany.



**Figure 3.** *The northern part of Møre and Romsdal County with the parking places marked with squares on the map*

Western Norway consists of a lot of fjords, mountains and islands, and to get from one point to another is not always straightforward. The use of Euclidian distances between the different points to create routes will not work very well because of the topology and dependence of ferries to cross fjords and get to the islands. In the last decades several tunnels and bridges are built to replace ferries and to straighten the roads, and these projects are often financed as toll roads. Because of rather high toll rates, it is desirable to restrict the passing of these toll gates to a minimum.

A distance table between the different locations was created using a database created by the Norwegian Mapping Authority. The locations are not public available, but the authors can help getting access to the table. The table does not directly consider ferries and toll roads, but in addition to the distance table this information could be considered as an extra cost on the routes. The extra cost is calculated as a constant value multiplied with the number of ferries on the tour and another constant multiplied with the number of toll road passings.

The remainder of this paper is organized as follows. Section 2 provides a review of similar problems from the literature and in Section 3 the definitions of our real-world problem is described. In Section 4, we first present the tabu search heuristic and then shows how the algorithm is adjusted to fit our problem. Section 5 shows the computational results, and the conclusions and suggestions for further research is given in Section 6

## 2. Related work

The real-world problem described in the previous section is closely related to other problems described in the literature. Chao (2002) and Scheuerer (2006) describe the *Truck and Trailer Routing Problem* (TTRP) as a variant of the traditional *Vehicle Routing Problem* (VRP). In this problem customers are divided into *vehicle customers* who can be reached with a complete vehicle with a trailer, and *truck customers* who only can be reached by a single truck. This means that there will be three types of routes in a solution of the problem: (1) a pure truck route travelled by a truck alone, (2) a pure vehicle route without any subtours travelled by a complete vehicle and (3) a complete vehicle route consisting of a main tour travelled by a complete vehicle and one or more subtours travelled by a truck alone. A subtour starts and finishes at a vehicle customer where the trailer is uncoupled and parked when the truck is driving the subtour.

Gerdessen (1996) presents the *Vehicle Routing Problem with Trailers*, which is related to the TTRP. In this paper all customers are reachable with trailers, but some are located on places where manoeuvring the complete vehicle is very difficult. The need for parking the trailer and driving subtours with a single truck will then be calculated as a function of the service time at the customers. This paper refers to another application from the dairy industry where it is profitable to use a truck with a trailer and park the trailer before some of the customers are visited. The Dutch dairy industry uses this strategy when distributing their products to customers which often could be located in crowded cities. Gerdessen (1996) assumes in her paper that each customer possesses unit demand and that each trailer is parked exactly once, so each tour will contain exactly one subtour.

Semet and Taillard (1993) consider a real-world VRP for a Swiss grocery chain when distributing goods to its stores. Some stores can be reached by a full vehicle with a trailer, while others can only be reached by a single truck, and the paper presents a tabu search based method for finding good solution to this problem that involves parking the trailer and driving subtours to the stores unreachable by the full trailer. Semet (1995) presents a mathematical model of the *Partial Accessibility Constrained VRP* (PACVRP). This model is quite similar to the TTRP used by Chao (2002) and Scheuerer (2006). The differences are that in PACVRP, each vehicle tour can only contain one subtour, and the depot can only be visited once in each tour.

Nag, Golden and Assad (1988) describes the *Site-Dependent VRP* (SDVRP) which is related to the TTRP. In this problem the company has several types of vehicles and the customers have restrictions on which type of vehicle it should be visited by. Customers with extremely high demand may require a large vehicle, while customers in heavily congested areas or located in difficult places may require small or medium sized vehicles. The paper proposes several heuristic procedures for solving this problem.

Tan, Chew and Lee (2006) describes the *Truck and Trailer Vehicle Routing Problem* (TTVRP) which unlike TTRP requires the truck to visit trailer exchange points for picking up the correct trailer types depending on the jobs to be serviced. A truck needs



to be accompanied by a trailer when servicing a customer. Trailers are left at the customer location for about two days and emptied (or filled if pick-up demands). Then a vehicle, which is not necessarily the same as the vehicle that left the trailer there, will pick it up and drive it to the depot. In TTVRP, jobs can be outsourced to external companies if not handled by the company's fleet.

The idea of using a mobile depot can also be found in other types of routing problems. Del Pia and Filippi (2006) describe a waste collection problem in Due Carrare, Northern Italy, which is a generalization of the Capacitated Arc Routing Problem. Here they divide between large vehicles (compactors) and small vehicles (satellites). Because of its size, the compactor can not traverse the narrowest streets in the town, and the problem consists of constructing compactor-tours and satellite-tours for collecting the waste. The tours will be constructed in a way that a satellite will meet a compactor at the same node at the same time interval, and then it can pour off its content to the compactor.

### **3. Problem definition**

Our real-world problem could best be described as a TTRP where all customers (suppliers) are defined as truck-customers. However, in contrast to the earlier described TTRP, it is also a multi depot problem in that milk from a supplier can have a choice of different dairies for processing.

Since the milk does not need to be collected each day, the same vehicle can drive different tours for different days. This periodicity is solved in the model by multiplying the number of vehicles available with the frequency of the visits. If a vehicle is driving the same tour every third day, this is planned as three different tours in the model and the amount to be collected is adjusted according to the number of production days. The model is described according to today's practice where no suppliers can be visited by a complete vehicle with a trailer. Every tour is attached to one dairy plant and will not deliver milk to other plants, even if such tours are possible to construct.

Some limitations from the real world situation are used in this model partly because not all information is known and also to reduce the problem to be solvable within the limited time available for this project. Further research on this case should try to implement these matters. At first, the dimension of time is not considered, and then neither is the cost of the tours in money. The tours are compared by a total distance cost which is similar to the distance driven but since the distance table do not specify ferries and toll roads, these matters have to be considered otherwise to reduce passing of these bottlenecks to a minimum. In the model, we have estimated the cost of using a ferry similar to driving 50 kilometres and passing a toll road similar to driving 25 kilometres and in the objective function these values are added to the driving cost when the tour passes one of these bottlenecks.

The model of the problem presented in this paper could be described by the definitions below.

1. The problem consists of a set of depots  $D$ , a set of parking places  $P$ , a set of suppliers  $S$  and a fleet of vehicles  $V$ .
2. Each depot  $d \in D$  should have delivered a minimum daily amount  $\zeta_d$ .
3. Each supplier  $s \in S$  has a certain amount of daily production  $\rho_s$ .
4. A solution  $\sigma$  to the problem consists of  $M$  routes of vehicles  $v \in V$  starting and ending at a depot  $d$  and visiting all suppliers in  $S$ .
5. The vehicles can be of different sizes. The capacity  $Q_v$  of the complete vehicle should not be exceeded on a full tour, and the capacity of the truck  $Q_t$  should not be exceeded on a subtour
6. The distance between all depots  $d \in D$ , parking places  $p \in P$  and suppliers  $s \in S$  are given in a distance table  $C$ .  $c_{ij} \in C$  gives the distance between nodes  $i$  and  $j$  where  $i, j \in D \cup P \cup S$ . The total driving cost of a solution  $\sigma$  is given by the function  $\gamma(\sigma)$ .
7. Extra costs for ferries and toll roads when driving between depot, parking places and suppliers are calculated from a table of extra costs  $E$ .  $e_{ij} \in E$  gives the extra costs between nodes  $i$  and  $j$  where  $i, j \in D \cup P \cup S$ . The total extra costs of a solution  $\sigma$  are given by the function  $\varepsilon(\sigma)$ .
8. A solution is defined as infeasible if the total load exceeds the vehicle capacity or the load on a subtour exceeds the truck capacity. In addition a solution is infeasible when the sum of the driving cost and the extra cost exceeds an upper limit or when the tours attached to a depot do not deliver the necessary amount  $\zeta_d$ . These solutions are accepted in the search with a penalty  $\beta(\sigma)$  to the calculated cost.
9. The objective function  $f(\sigma)$  of a solution is to minimize the cost of all tours.  

$$f(\sigma) = \gamma(\sigma) + \varepsilon(\sigma) + \beta(\sigma)$$

In addition the following assumptions are used to describe the problem.

10. Every supplier is served by exactly one vehicle.
11. Milk from a supplier can be delivered to different depots, although not on the same tour.
12. No suppliers can be reached with a truck carrying a trailer.
13. When using truck with a trailer the depot should be visited only once.
14. Tours using only a truck may consist of several subtours from the depot.
15. A tour should start and end at the same depot and can not deliver milk to another depot in the same tour.

16. A trailer tour consists of a tour between possible parking places and subtours from those with the truck as shown in figure 2.
17. A trailer can be parked several times and several subtours can be driven from each parking place.
18. Parking places are separate entities and not attached to any customer.
19. A parking place is only used if it is favourable. Parking places do not have to be visited as they have no demand, and the model chooses the best parking place from the set  $P$  which may contain more parking places than needed.
20. When creating the tours, the planners will not take time windows for the visit into consideration. This is managed by the drivers of the vehicles in agreement with each farmer.
21. When planning tours where the suppliers not are visited every day, each day is treated as a separate tour and the amount to be collected are adjusted according to the frequency of the visits.
22. The model considers no extra cost for driving with a trailer compared to a single truck. Neither is the speed considered different if the trailer is attached the vehicle.
23. All ferries are treated in the same way with a constant added to the cost function. This is independent of the length of the ferry distance, the fare, the departure frequency or if the trailer is attached. This addition to the cost function is necessary to avoid superfluous ferry trips.
24. The toll roads are similarly treated as ferries with a constant added to the cost function.
25. The driving time is not considered in the model, but there is a constraint that the sum of the driving cost and extra costs of a feasible tour should not exceed an upper limit. This constraint will prevent the tours from being too long.

#### **4. Tabu search metaheuristic**

Tabu search is a well-known metaheuristic which first was proposed by Glover (1986) and is described in Glover and Laguna (1997). The method is developed from the traditional greedy local search where the search moves from one solution to a better one by performing a move which is defined as a small change of one or more of the attributes in the incumbent solution. All the possible new solutions that can be reached by one move are defined as the neighborhood of the incumbent solution. While the greedy local search will stop at a local optimum when it cannot find any improving moves, tabu search is able to proceed beyond the local optimum and continue the search by moving to poorer solutions. To avoid that the search is returning to solutions it has explored earlier, the attributes of the moves most recently performed are declared tabu, and the move is not allowed again until after a certain number of other moves have been

performed. However, if some aspiration criterion is satisfied, a move declared as tabu could be executed anyway. Typically this could be if the move leads to a solution better than any other found in the search.

#### **4.1 Parameter tuning**

To exploit the advantages of tabu search in the best possible way, it is necessary with a careful calibration of the parameters used in the search. During the test phase to find the right parameter values to use, suppliers from one of the original tours used by TINE BA on each of the three dairy plants were selected. This made a total of 185 suppliers which is about 19% of the size of the full problem. The preliminary tests to find the best possible parameter values were run with two different vehicle types; a truck with capacity of 10000 litres combined with a trailer with capacity of 11000 litres, and a single truck with capacity of 18500 litres. The tests with the truck and trailer were run with a frequency of “7x3” while the tests with the single truck were run with a frequency of “7x2”. All tests were run for 5000 iterations from three different random starting solutions. By looking at the results of the different searches, it is possible to suggest the parameter values that should be used. If all three runs for both vehicle types and frequencies showed similar results, the conclusion was simple. For some parameters however, the search results were ambiguous and in such situations the value which showed best results overall for the strategies used in the test was chosen for the subsequent tests.

##### **4.1.1 Initial solution**

Creating an initial solution is an important step in the process of obtaining good solutions from a search. Cordeau et. al. (2002) and Laporte et. al. (2000) describes several construction heuristics for VRP solutions. Scheuerer (2006) presents two different heuristics called *T-Cluster* and *T-Sweep* for the construction phase. The *T-Sweep* heuristic is based on the classical sweep algorithm first suggested by Gillett and Miller (1974). It will sort the nodes by an angle from the depot and an arbitrary line routed at the depot, then rotates a ray and sweeps the suppliers to the same tour when they are touched by the ray as long as the tour is feasible. When a tour is filled, it will be closed and a new tour will be started from the same angle that the last tour ended. This method is best suited for planar instances with a central depot, and is not very suitable for our problem where a large mountain or a fjord could separate suppliers with the same angle to the depot.

The *T-Cluster* heuristic is however, with some adjustments, a better alternative for our problem. Here every tour in the solution is constructed by containing one *seed order*, and then the other orders are assigned to the tours by solving a *Generalized Assignment Problem* (GAP). This strategy is suggested by Fisher and Jaikumar (1981) and used by several others in similar VRPs.

The selection of seed-orders could be done in several ways. Semet and Taillard (1993) select first the orders with volume larger than the half capacity of the vehicle. Then, if the number of such orders is less than the number of tours, the farthest order

from the previously selected seed order is selected. This is repeated until the desired number of seed orders is reached. The strategy of selecting orders with large volume could however not be used in our problem, as all orders have a volume far less than the vehicle capacity. Other possibilities for selecting seed orders suggested by Fisher and Jaikumar (1981) are to use the order which is furthest away in each *radial corridor* from the depot, or to let a scheduler with knowledge of the problem choose the seed orders manually.

In GAP, orders are assigned to tours by minimizing the additional cost it will take to include the order in the tour. Semet and Taillard (1993) calculates the coefficients  $c_{ik}$  in the GAP by the following formula:  $c_{ik} = d_{0i} + d_{ii_k} - d_{0i_k}$ . Here  $c_{ik}$  is the cost of including order  $i$  in tour  $k$  and is computed as the extra distance for serving order  $i$  compared to driving directly to the seed order  $i_k$ . Scheuerer (2006) uses a slightly different formula to compute the additional cost:  $e(k) = c_{ku} + c_{kf} - \pi c_{0k}$ . Here  $e(k)$  is the cost of adding order  $k$  to the tour, when looking to the border of the tour and not only the seed customer.  $c_{ku}$  measures the distance from order  $k$  to the seed order  $u$ , and  $c_{kf}$  is the distance from  $k$  to the nearest order  $f$  which is already in the tour. The last term in the formula consist of the distance between the depot and order  $k$  multiplied with parameter  $\pi$ , where  $\pi$  is considered as a diversification factor which could be adjusted to higher values if one wants to select orders located far away from the depot.

The strategy of using the distance to the tour as a measure for choosing which orders to add to the tour does, however, not work very well for our real-world problem in Western Norway. This is mainly because of the geographical conditions with a limited number of roads. Farms close to the main roads could be added to any tour because the vehicles will use the same roads to get to the districts, while more distant farms up in the hillsides and islands might not as easy be attached to the right tour.

What turned out to be the best way to create initial solutions in our problem is to select seed orders by a combination of preliminary knowledge represented by TINE BA's current tour structure and the distances from other seed orders and the depot. Then the other orders are clustered by distance to the seed orders, and if the total amount in a cluster exceeds the total vehicle capacity for the tour, the order furthest away are expelled and forced to cluster to another tour. In this process one also has to ensure that the tours connected to each of the three dairy plants will contain the necessary amount of milk that the plant need each day.

By looking at the current tour structure and the amount of milk collected on these tours, it is easy to calculate the share of the total amount for each of these tours. When creating a new tour structure with other vehicle types, the first thing to do is to find the necessary number of tours according to the new vehicle fleet. We know that we need one seed customer for each of the new tours, and by using the shares calculated for the current tours, we can easily compute the number of seed orders that should be selected from each of these tours. The first seed order to be selected from a current tour is the one being furthest away from the depot, and the second seed order will be the one with the largest total distance from the first seed order and the depot. For an eventual third,

and in the cases where a fourth or fifth seed order is needed, the total distance from the previously selected seed orders are used according to Semet and Taillard (1993). The distance from the depot is not included at this point and the third seed order will then usually be the one nearest the depot in the current tour. This is not necessarily bad, and our tests show that if the distance to the depot is included, the third seed order will often come close to the first one which could be in a solitary valley or an island. In such cases, the long distance from the depot will dominate over the short distance between the two seed orders. When the seed orders for the tours are chosen, the other orders are assigned to the vehicles serving each tour.

When clustering of the orders to the tour is completed, it is necessary to find a favourable way to serve these orders with the available vehicle. This can be done by solving a *Traveling Salesman Problem* (TSP) for the orders in the tour using a local search with a 2-opt neighborhood as described in Lin (1965). The result of this search is not necessarily the optimal TSP-tour, but it should be of sufficient quality at this stage of the search. For tours served with a truck and trailer, we do in addition have to find the best positions for the parking places and make subtours for the truck. The strategy for inserting parking places is to run through all the orders sequentially and insert a parking place at the position where the aggregated amount of the orders exceeds the truck capacity. Then a new subtour is started by running through the remaining orders and inserting new parking places at the next position where the aggregated amount exceeds the truck capacity and so on. If a bottleneck like a ferry or a toll road is passed, parking places are inserted even if the truck capacity is not exceeded. This is to avoid subtours where the truck has to pass the bottleneck twice. A clustering strategy like the one used when creating the main tours did not work as well on the subtours as the one described above. Another strategy is to compute the necessary number of subtours by dividing the truck capacity to the total amount for orders on the tour and then distribute the same number of orders to each subtour. This strategy did neither get results of the same quality as the one described.

When the parking places are inserted and the subtours then are defined, each subtour has to be re-optimized as a TSP-tour using the same 2-opt local search as optimizing the full tour, and at last the parking places have to be recalculated to see if there are any better positions than those first selected.

A detailed description step by step of the algorithm for making initial solutions can be found in Appendix B.

#### 4.1.2 Neighborhood structure

The neighborhood  $N(\sigma)$  to a solution  $\sigma$  is defined as all possible solutions that can be obtained by applying one move from the solution. A move can be defined in several ways for the VRP and related problems. Osman (1993) proposes a  $\lambda$ -interchange neighborhood for the *Capacitated Vehicle Routing Problem* which could be used in our problem. In this neighborhood two tours  $q$  and  $r$  are selected together with two subsets of orders  $S_q$  and  $S_r$  from each tour satisfying  $|S_q| \leq \lambda$  and  $|S_r| \leq \lambda$ . The operation swaps the orders in  $S_q$  with those in  $S_r$  as long as this is feasible. The operation includes the

possibility of moving one order from one tour to another by allowing one of the sets to be empty.

In this paper we will use the  $\lambda$ -interchange neighborhood where  $\lambda=1$ . This means that a move can be defined in two different ways: a *shift move* which is when an order is selected from one tour and inserted into another or a *swap move* which is when two orders from different tours are selected and swapped between the tours. This is a neighborhood with a huge number of possible moves. With 990 orders in our problem instance and the possibility that each order can be shifted to all alternative positions which includes before or after a parking place and insertion to a new subtour, this will mean around 1 million neighbors. The possibilities of swapping the order with an order in another tour will almost double this number. By using a higher value of  $\lambda$  the number of neighbors will increase even more. It is obvious that we need a way to decide which moves that should be tried and which moves that could be omitted without having to calculate the objective value of each of the following solutions.

Other definitions of the neighborhood are possible. Semet and Taillard (1993) use a neighborhood where each order is removed from the tour it belongs, and try to insert it into another tour. In their real-world problem from a Swiss grocery chain they operate with up to 90 orders from 45 grocery stores. Chao (2002) uses a neighborhood with possibilities of both moving and swapping orders between tours and in addition he defines another type of move which is changing the parking place which serves as the root of the subtours. Scheuerer (2006) introduces the possibility of moving or swapping subsets of consecutive orders in addition to single orders. This can be regarded as a restricted  $\lambda$ -interchange neighborhood where the orders has to retain the same consecutive sequence. To reduce the neighborhood he only considers moving or swapping orders to tours which contain other orders which are close to the first order in the sequence. To reduce the neighborhood even more, the evaluation of possible moves is restricted to a candidate set  $M(\sigma)$  which is randomly selected at each iteration among all orders in the solution  $\sigma$ . Chao (2002) and Scheuerer (2006) uses examples up to 200 orders in their tests, which means that their cases are less than 20% of size compared to our real-world case with 990 orders and 37 parking places.

In our search we don't define the change of parking places as a separate move. Since parking places in our problem are separate entities which do not have to be visited, this operation is included in the re-optimization procedure of a solution. We also restrict the possible shift or swap to single orders, but the possibility of extending the neighborhood to include clusters of orders or even whole subtours is interesting and should be explored further in some later work.

### **Reducing the neighborhood**

For problem instances with a great number of possible moves, techniques have been developed for not having to evaluate all the possibilities before performing a move. Toth and Vigo (2003) describes the *Granular Tabu Search* which restricts the neighborhood by excluding the moves that include attributes that are not likely to belong to good feasible solutions. As mentioned above, Scheuerer (2006) reduces the

neighborhood by only considering moves to tours which have orders close to orders in the current tour. He introduces an *h-neighborhood* to each order (in our case a supplier)  $s \in S$  which consist of the  $h$  orders closest to  $s$ . This technique for neighborhood reduction could be adopted to our problem. If a tour or a subtour does not contain one of the  $h$  closest orders to the one we try to move, it is of no use to try to insert it into that tour.

Since a move consist of shifting or swapping only one order in a tour, many possible moves can be eliminated if we find a way to prioritize between the members of a tour and select the one with highest priority. The *h-neighborhood* could also be used for this purpose. By counting how many of an order's *h*-neighbors which are outside the current tour, it is possible to find an indication on which order to select for a possible move. The order with most *h*-neighbors outside its own tour should have the highest priority to be selected. When an order is selected both possible move types are tried with that specific order. First, a shift move is tried into all tours containing at least one *h*-neighbor of the selected order by inserting the chosen order next to the closest order in the new tour. Second, a swap move is tried with the same tours. The swapping order from the other tour is picked by random among the orders in the same subtour as the closest order.

Our preliminary tests showed that  $h = 10$  is a sufficient value to use in our search. These tests showed no improvement of the search results when  $h$  are increased beyond this value, but the searching time increases significantly when  $h$  gets larger.

### **Partial neighborhood examination**

Even with the reduction of the neighborhood mentioned above, the number of possible neighbors is large and a complete analysis of all those in each iteration will be very time consuming. Semet and Taillard (1993) suggest a strategy for reducing the computation time by only looking to a part of the neighborhood for each iteration. These ideas are also used by Voudouris and Tsang (1999) in Fast Local Search. In their example, Semet and Taillard (1993) use the following formula to decide which orders that should be considered in iteration  $k$ .

$$O_{(((k-1)\lfloor n/\varphi \rfloor) \bmod n)+1}, O_{(((k-1)\lfloor n/\varphi \rfloor+1) \bmod n)+1}, \dots, O_{((k\lfloor n/\varphi \rfloor-1) \bmod n)+1}$$

where  $n$  is the total number of orders and  $\varphi$  is the number of parts the neighborhood is divided into, which in their example is equal to four.

By looking at tours instead of orders, this strategy can be used for our problem. To decide the necessary size of  $\varphi$ , several tests were run on the selected test case which consisted of about 19% of the total suppliers. Our tests show that the results for  $\varphi = 2$  is even better than the result for  $\varphi = 1$ , which indicates that exploring a smaller part of the neighborhood might in some cases be in preference to using the whole neighborhood.  $\varphi = 2$  corresponds with a neighborhood covering four out of eight tours and six out of twelve tours with the vehicle types used in our test cases. However, on the test case with twelve tours the result with  $\varphi = 4$  only differs with 2% from the result found with  $\varphi$



= 2 while the searching time is almost halved. On the test case with eight tours, we can not conclude the same way as the result with  $\varphi = 4$  is more than 7% above the result with  $\varphi = 2$ . Our conclusion is that we need to examine about three tours in each iteration to make it effective. As reducing searching time is of great importance in making this problem solvable in reasonable time, the value of  $\varphi$  for our final tests is calculated so that there will be about three tours in each subset. One important aspect when examining the partial neighborhood this way is to take the value of  $\varphi$  into consideration when calculating the tabu tenure, as the orders in the current tour will not be considered for a move until the next time the tour is within the part of the neighborhood that are examined.

### **Selecting a move**

The strategy for selecting a move in each iteration in the search is to compare the possible shift and swap moves for the chosen order in each of the tours that are evaluated in that iteration. Tabu restrictions and diversification to avoid that the same order is chosen every time are explained later. When inserting an order to another tour, it is necessary with a short re-optimization of the tour to be able to fairly compare the new solution with others. How extensive the re-optimization should be is a trade-off between the quality of the solution and the computing time. In our tests, a short local search is run by trying to move the last order in the changed subtour to other subtours as long as this is profitable. By this way we will avoid situations where adding an order will make a subtour infeasible, while other subtours in the tour have enough space. After the local search is performed, a check is done to see if the parking places could be replaced with someone better. This is particularly important in cases where the last order in a subtour is removed, to avoid that the vehicle will drive to a parking place with no potential orders to serve.

### **4.1.3 Number of iterations**

We can assume that a plan will need about the same number of vehicles regardless of the visiting frequency to each supplier. The total amount of milk produced each day, and the total vehicle capacity will be the same even if the suppliers are visited every day, every second day or every third day. A plan with a visiting frequency every third day will then consist of three times as many tours as a plan with visiting frequency every day. The number of suppliers visited in each tour will correspondingly roughly be three times as large on the one day frequency tours as on the three day frequency tours. This makes the computing time for each iteration larger with short visiting intervals than with large ones since the evaluation procedure includes a TSP-optimization of each subtour.

Since the partial neighborhood examination discussed in Section 4.1.2 concluded that about three tours should be considered in each iteration, the need for more iterations in the search will be higher for solutions with many tours than for solutions with fewer tours. Our preliminary tests show that the best solution is usually found early in the search, and our conclusion is that 1000 iterations normally should be sufficient to find

solutions of acceptable quality. When adjusting to the visiting frequency, the number used in our final tests are 1000 iterations for one-day intervals, 2000 iterations for two-day intervals and 3000 iterations for three-day intervals.

#### 4.1.4 Tabu Tenure

When an order is inserted into a tour it will be declared tabu from moving for the next  $\theta$  iterations where  $\theta$  is the tabu tenure. It will not be selected for a possible move unless all other orders in the tours are tabu too. It is however possible that a tabu order could be selected randomly for a swap with an order in another tour.

Glover and Laguna (1997) claim that a variable value of  $\theta$  can be better than a fixed one, and our preliminary tests on the selected test cases showed best results with a variable tabu tenure in the interval [8, 16]. This value was found with  $\varphi = 2$  in our test cases, and to get the effective tabu tenure one has to adjust by the value of  $\varphi$  used in the search. Cordeau, Gendreau and Laporte (1997) state that  $\theta$  should be set in relation to the instance size, and our full problem is about five times as large as the selected test case. When using partial neighborhood examination to the problem, it is, however, not obvious how the size of the full problem should affect the tabu tenure. We have thus decided to ignore the instance size when determining  $\theta$ , and our subsequent tests were run with  $\theta$  selected randomly in the interval  $[4\varphi, 8\varphi]$  where  $\varphi$  is the number of parts in the neighborhood examination

#### 4.1.5 Penalty for infeasible solutions

Considering infeasible solutions can in many cases make it easier to overcome obstacles in the search. The way to deal with those solutions is to add a value to the objective function proportional to the amount of infeasibility with respect to some constraints. In our problem infeasibility can be observed in three different ways

- a. The tour cost including the additional cost computed when passing ferries or toll roads exceeds a distance limit.
- b. One or more of the depots don't get enough delivery from the tours attached to them.
- c. The total load on a tour exceeds the vehicle capacity or the load on a subtour exceeds the truck capacity.

Point 8 in the model described in Section 3 introduces a penalty value  $\beta(\sigma)$  for an infeasible solution  $\sigma$ . We consider situations a and b to be unwanted in our search, and solutions violating those constraints are punished with a large, static value of  $\beta(\sigma)$  to avoid that they should be selected, or force the search back to a feasible solution if they are selected anyway. Situation c, with the violation of the truck load, is however more interesting to consider as those solutions more probably could be an intermediate stage between two good feasible solutions. To be able to oscillate between feasible and infeasible solutions, a dynamic penalty factor is introduced and adjusted during the search. The formula for calculating the penalty for overload is inspired by the similar

formula found in Gendreau, Hertz and Laporte (1994) and adjusted to fit to our problem.

$$\beta(\sigma) = \alpha \left( \sum_r (L_r - Q)^+ + \sum_r \sum_{i \in R_r} (L_{ir}^t - Q_i)^+ \right).$$

$\beta(\sigma)$  is the penalty for solution  $\sigma$  which are added to the objective function and  $(x)^+ = \max\{0, x\}$ .  $r$  is all tours in the solution, while  $R_r$  are all subtours in tour  $r$ .  $Q$  is the capacity of the complete vehicle and  $Q_i$  is the capacity of the truck, while  $L_r$  is the total load in tour  $r$  and  $L_{ir}^t$  is the truckload on subtour  $i$  in tour  $r$ . Penalty factor  $\alpha$  is initially set to 1 and adjusted during the search by multiplying or dividing it with a value  $\kappa$  when the solution is respectively feasible or infeasible. Preliminary tests show that the value  $\kappa = 1.1$  gives best results in our search.

#### 4.1.6 Diversification

Diversification strategies are often used in tabu search to avoid that the same moves are performed too often. In our search, selection of the order that should be tried to move from each tour is done by counting the number of  $h$ -neighbors in the tour, and choosing the one with least  $h$ -neighbors inside its own tour. In this process diversification could be used to avoid that the same order is selected each time. A counter is introduced to count the number of times each order is chosen from each tour, and this counter is multiplied with a diversification factor  $\eta$  and used in the process of selecting orders by using the formula

$$\xi(s) = \psi(s) + \eta \tau(s)$$

$\psi(s)$  is the number of  $h$ -neighbors order  $s$  has inside its own tour, while  $\tau(s)$  is the number of times order  $s$  is selected from the current tour. The order  $s$  with lowest value  $\xi(s)$  is selected for an eventual move from the tour as long as it is not declared tabu.

Our test results are not unambiguous about the value of  $\eta$ . Some tests indicate that it should be as small as possible (or preferably absent), while other tests show best results with a value between 0.5 and 1. We have chosen to use the value  $\eta = 0.75$  for our subsequent tests, as this value gave a slightly better result than the other alternatives.

The final algorithm for the search is described step by step in Appendix A.

## 5. Computational results

The search algorithm described in Appendix A was coded in C++ and run on a Pentium 4 2.40GHz computer with 512 RAM running Windows XP.

Table 1, 2 and 3 shows the result from a search with the different strategies and standardized vehicles. The vehicle types used in the test are some of the vehicle types used by TINE BA today. Note that larger combinations of trucks and trailers than showed in the table are not permitted because of restrictions on vehicles driving on the Norwegian road network.

**Table 1.** Result of the search with different vehicle types and visiting frequency every day

ID	Q <sub>v</sub>	Q <sub>t</sub>	Q <sub>x</sub>	Freq.	M	Ξ	Π	T <sup>s</sup>	Obj.value
1	10000	10000	0	7x1	33	-	-	133	9899.09
51	14500	14500	0	7x1	23	-	-	166	7721.74
5	18500	18500	0	7x1	18	-	-	194	6683.52
12	21000	10000	11000	7x1	16	2,75	1,88	278	8301.66
17	29000	10000	19000	7x1	12	3,08	2,25	421	7593.90
71	33500	14500	19000	7x1	11	3,00	2,45	482	7799.11
36	29500	18500	11000	7x1	12	2,17	1,92	378	6922.29
39	33500	18500	15000	7x1	11	2,55	2,09	451	6857.01

**Table 2.** Result of the search with different vehicle types and visiting frequency every second day

ID	Q <sub>v</sub>	Q <sub>t</sub>	Q <sub>x</sub>	Freq.	M	Ξ	Π	T <sup>s</sup>	Obj.value
1	10000	10000	0	7x2	64	-	-	126	7863.78
51	14500	14500	0	7x2	45	-	-	119	5792.62
5	18500	18500	0	7x2	36	-	-	115	5188.69
12	21000	10000	11000	7x2	32	2,75	1,63	167	6091.19
17	29000	10000	19000	7x2	24	2,96	1,75	199	5393.38
71	33500	14500	19000	7x2	22	2,50	1,82	200	4783.50
36	29500	18500	11000	7x2	24	1,88	1,38	162	4976.25
39	33500	18500	15000	7x2	22	2,23	1,55	187	4629.29

**Table 3.** Result of the search with different vehicle types and visiting frequency every third day

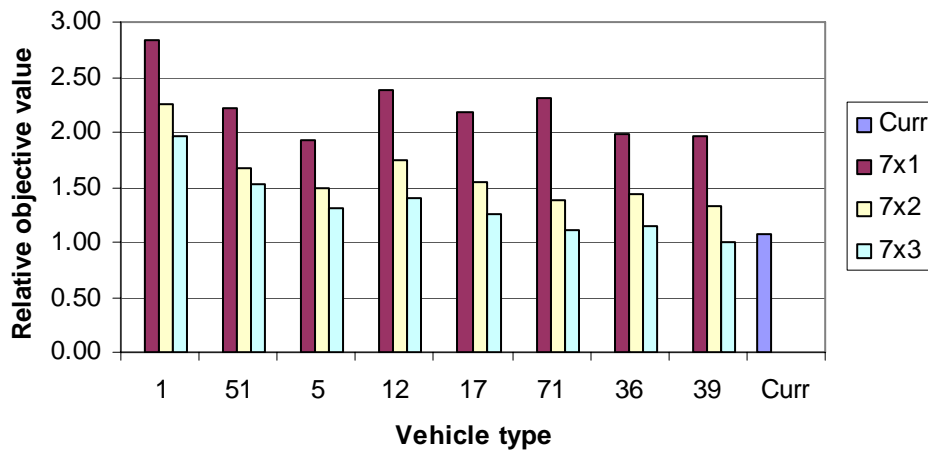
ID	Q <sub>v</sub>	Q <sub>t</sub>	Q <sub>x</sub>	Freq.	M	Ξ	Π	T <sup>s</sup>	Obj.value
1	10000	10000	0	7x3	95	-	-	177	6849.45
51	14500	14500	0	7x3	68	-	-	123	5312.21
5	18500	18500	0	7x3	53	-	-	126	4526.99
12	21000	10000	11000	7x3	47	2,68	1,62	144	4856.26
17	29000	10000	19000	7x3	36	3,06	1,69	182	4347.30
71	33500	14500	19000	7x3	32	2,66	1,59	143	3875.62
36	29500	18500	11000	7x3	35	2,09	1,46	144	3975.95
39	33500	18500	15000	7x3	33	1,97	1,48	142	3480.90
<b>Curr.</b>	-	-	-	-	32	2,22	1,22	-	3764.36

The first column in the table shows the id-number of the vehicle used, while the next three shows the capacities of the vehicle. Q<sub>v</sub> is the total capacity, while Q<sub>t</sub> is the capacity of the truck and Q<sub>x</sub> the corresponding capacity of the trailer. The next column shows the frequency code of the tours. The last five columns show the result of the

search.  $M$  is the number of tours in the best solution found, while  $\Xi$  is the average number of subtours and  $\Pi$  is the average number of parking places used on each tour served by a truck with trailer.  $T^s$  is the searching time per iteration in seconds and the last column shows the objective value which is the tour cost with the computed extra cost for passing ferries and toll roads of the best solution found. For comparison the similarly computed objective value for the current tours used by TINE BA is shown in the row with id *Curr*. The current tour strategy uses various frequencies and vehicles on the different tours.

### 5.1 Tour frequency and vehicle capacity

The results from Table 1 with the objective value divided to the best found solution are shown in Figure 4.



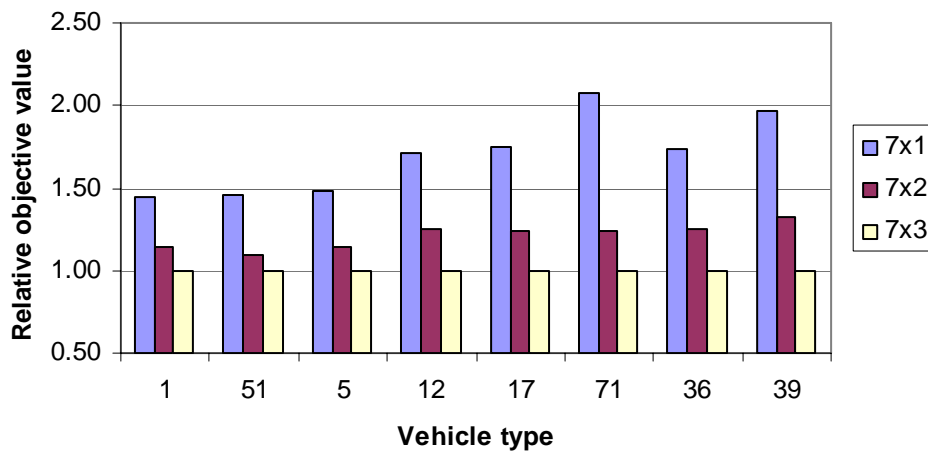
**Figure 4.** Comparison of different strategies and vehicle types

The figure shows clearly that for all kinds of vehicles there is an improvement of the solution found when the visiting frequency is extended. Solutions with a longer visiting frequency should then be preferred whenever possible

The best solution from the search are found when using the “7x3” interval with vehicles of type “39” which is a truck of capacity 18500 and a trailer with capacity 15000 litres. This is the largest of the vehicle types in the test together with type “71” which is a truck of capacity 14500 and a trailer with capacity of 19000 litres. The two vehicle types with the same total capacity shows however a significant difference in the solution quality. When comparing the solutions, we can see that the solution for type “71” is more than 11% poorer than the solution for type “39”. The same tendency can be seen with vehicle types “17” and “36” which has a total capacity of respectively 19000 and 19500 litres. It is evident that the combination with larger trucks compared to the trailer gives better solutions than the opposite. In such solutions the tours will contain larger and possibly fewer subtours which again leads to better solutions overall.

Another observation is the tendency that using larger vehicles gives better solutions than using smaller ones. This is obvious for single trucks, but when comparing to the different truck and trailer combinations, the conclusion is however not that simple. For all three intervals, the single truck of type “5” and capacity 18500 gives a better result than the combination of an 11000 litres truck and a 10000 litres trailer even if the total capacity of this solution is larger. Another interesting fact is that with a “7x1” frequency where all suppliers are visited every day, the solution found using single trucks with a capacity of 18500 litres each is even better than a solution with complete trucks and trailers of type “39”. By looking at the total capacity of the fleet, we can see that there probably is room for improvement on the solution with type “39”, but the tendency is anyway that single trucks does better compared to larger vehicles with trailers when the frequency gets short. When a problem consist of many suppliers with a small demand each, each tour will serve more suppliers and will cover a larger geographical area. The subtours of the truck and trailer combination will in such cases get larger and in addition the number of subtours will increase. Even if the tour stays within the upper limit for the driving cost of a tour, the distance between the parking places can be so large that it might be as profitable to skip the trailer and rather drive the tours with single trucks.

Figure 5 shows the solution found with the different frequencies for each of the vehicle types divided to the best solution found for that type. The figure shows clearly that the advantage of extending the frequency increases in proportion to the total capacity of the vehicle.



**Figure 5.** Advantage of extending the frequency of visits for different vehicle types

When looking at the solution found by using the original distribution to the tours used by TINE BA, we can see that it is 8.1% poorer than the best found solution with all vehicles of type “39”. The current tour strategy has a total of 32 tours when adjusted according to the number of production days. The smallest plants at Høgset and Tresfjord use a “6x2” strategy for their tours. This is clearly an ineffective strategy as

the tours have to be planned for three days of production but the tours will be driven with less truck load on two of the three tours each week. The cost of such a solution could roughly be found by taking the corresponding solution with a “7x3” interval and multiplying it with 9/7 as in a three week period a “6x2” strategy would have driven the tour nine times, while a “7x3” strategy would have driven it seven times. The largest plant in Elnesvågen uses the “7x3” strategy for the suppliers with largest distance from the plant, but for the nearest suppliers the “7x2” strategy are used. The conclusion following our test results is that with existing tours with a shorter frequency than “7x3” one should consider to extend the frequency and make investments in larger cooler tanks where this is needed.

For some of the tours in the neighboring districts to the dairy plants, the tours planned with trailers will end up with optimal parking place located at the plant. This corresponds to solutions where a single truck drives several subtours from the depot without a trailer. Combinations of single truck and truck with trailer solutions are also possible where a trailer is used on a few subtours, and the vehicle returns to the plant and drives another subtour from there or another possibility is a solution where the truck drives single tours from the depot one day and uses the trailer for the tour another day. Thus, a more flexible approach than one specific type of vehicle for all tours is possible to achieve even within the framework of the algorithm presented in this paper, and by analyzing each tour separately, one can conclude that some of them are possible to serve with a smaller vehicle than the type used in the search.

Our tests indicate that with a similar total capacity of the vehicle, better results are achieved with relatively more capacity on the truck than on the trailer. This will make the subtours larger and then the number of subtours will be reduced and as a consequence the need for parking places will be reduced as well. TINE BA uses the combination of trucks with  $Q_t = 14500$  and  $Q_x = 19000$  on several of their tours, but by changing this to a combination of  $Q_t = 18500$  and  $Q_x = 15000$  the total capacity for the vehicle is retained. Most of the trucks in the company’s fleet are with three axles and can hold a maximum tank load of 14500. A change of vehicle types will then mean a major investment in trucks with four axles which can carry the larger tanks without breaking the restrictions of allowed axle pressure of the roads, but the advantage is the possibility of getting better tours by using the new vehicle type.

## **5.2 Parking places**

Finding the optimal parking places for the subtours is an important issue of getting good solutions. A tour will rarely consist of more than four subtours. The exception is some of the tours generated with a small truck compared to the trailer, but this is a combination proven not to create very good solutions. On the best solution found, using vehicle type “39”, the average number of subtours on each tour is nearly two and the average number of used parking places are about 1.5. Thus, about half of the tours will use the same parking place as root for different subtours.

The possibility of using different parking places for different subtours is clearly an advantage which affects the total driving cost. However, in the cases where the same

parking place can be used as root for several subtours, the time used for coupling and uncoupling the trailer can be reduced and this can be an alternative to consider if the difference is small. Table 4 shows the result of a search with the demand that one parking place should be the basis of all the subtours in the same tour. The rows marked with “71<sup>P</sup>” and “39<sup>P</sup>” contain the results of a search using vehicle type “71” and “39” with this extra constraint, while the results for the similar search without the constraint are shown for comparison.

**Table 4.** Comparison of the search result with and without the demand of using only one parking place

ID	Q <sub>v</sub>	Q <sub>t</sub>	Q <sub>x</sub>	Freq.	M	Ξ	Π	T <sup>s</sup>	Obj.value
71	33500	14500	19000	7x3	32	2,66	1,59	143	3875.62
71 <sup>P</sup>	33500	14500	19000	7x3	33	2,55	1,00	157	4292.43
39	33500	18500	15000	7x3	33	1,97	1,48	142	3480.90
39 <sup>P</sup>	33500	18500	15000	7x3	32	1,88	1,00	145	3968.38

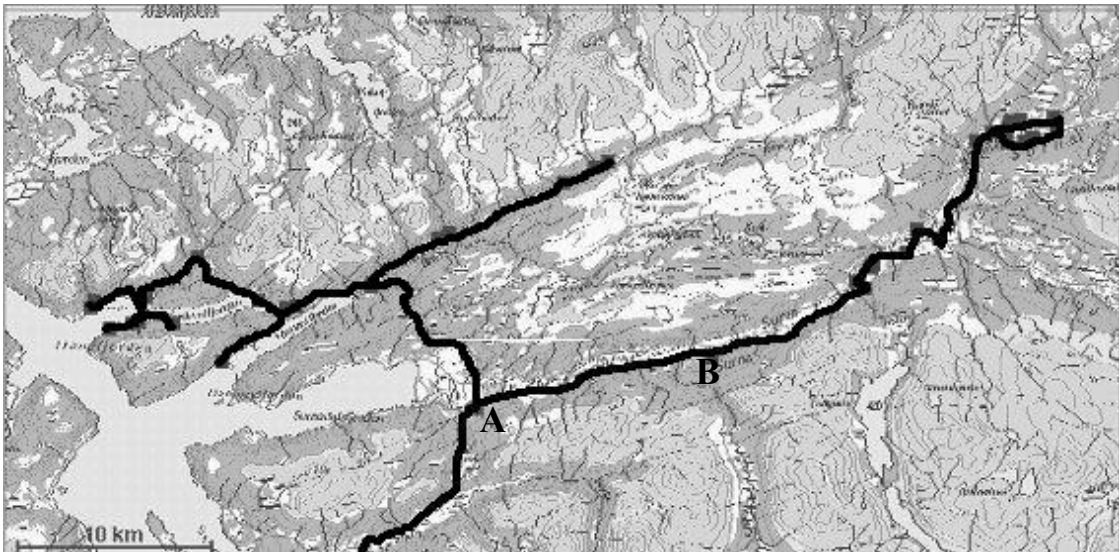
Our tests show clearly that allowing several parking places on the tours makes better solutions than with a demand that all subtours should start and stop at the same spot. This is even more evident for a vehicle combination of a large truck and smaller trailer than the opposite. The search with vehicle type “39” shows a result which is 14% poorer if the subtours are forced to have the same root, while the search with vehicle type “71” shows a result which is only 10% poorer with the same demand. This seems rather odd, because intuitively one should think that a solution which contains more subtours should gain more when saving the extra distance to drive to the common parking place. The reason is, however, that the structure of the solutions found in the search will be different when adding the extra constraint of a common parking place, and solutions with smaller subtours are better fit to avoid numerous passings of the ferries and toll roads than solutions with larger and fewer subtours.

Figure 6 shows one of the tours found by the search using vehicle type “39” and the “7x3” frequency. This tour is within the Surnadal and Rindal municipalities which are in the north-east of the county. It is a rural district with a large number of farms and this tour is one of five tours in the solution serving this area. As we can see, the geographical conditions limits the number of possibilities to get from one point to another, and instead of driving round trips the tour will mostly use the same roads back and forth when driving up in the valleys and along the fjords.

On this tour, the vehicle will come from the Elnesvågen dairy plant which is about 100 km. south-west of the lower border of the map including one ferry tour. It will arrive at the centre of Surnadal, leave the trailer at the parking place marked “A”, and then collect milk from the suppliers at the north-west of the map. Then the truck will return to the trailer at point A and move the trailer to point “B” before it visits the suppliers in the north-eastern part of the map. This is an example of a situation where the same parking place should be used for both subtours even if the search suggests



another solution which is shorter. Since parking place “B” is just along the main road, there is no extra distance to drive to this spot since the vehicle is driving the road anyway. Parking place “A” is however a short detour away from the main road, although it is only a few hundred meters. By using “A” as root for both subtours, one will get a solution which is slightly poorer when looking at the driving cost, but from a practical point of view it is preferable because one will save the time and effort it is to couple the trailer.



*Figure 6. One tour in Surnadal and Rindal municipalities*

In general it is better to allow several parking places than to force the tours to use the same parking place for all subtours. However, in farming areas with a high density of suppliers, using the same parking place for several subtours should be an option to consider and should be seen in relation to the time used for coupling and uncoupling the trailer.

## **6. Conclusions and further research**

In this paper we have developed a tabu search heuristic for solving a large real-world problem for milk collection in the Norwegian dairy industry. The heuristic is used to construct possible solutions to the problem with different strategies, and compare the solutions with each other and the current tour structure used by the dairy company. We have shown that using a strategy with trailers used as mobile depots and trucks driving subtours from the trailer spots is superior to a strategy using only single trucks. The reason for this is mainly because of the possibility of increasing the total load beyond the size of a single truck. We have also shown that a visiting frequency of every third day gives a better result than a shorter frequency and that existing tours might be improved by extending the frequency.

The heuristic developed is however rather time consuming because of the size of the problem and the large amount of calculation to find the objective value of the different alternatives in the search. Even if creating a tour strategy is not an every day job which is done under strict time requirement, further work on this problem should focus on reducing the searching time. One option is to use preliminary knowledge of the problem to reduce the problem size by clustering nearby orders and treat them as one single order. A more focused neighborhood that can find indications on which tours to select for eventual changes can be another option. The filling degree of a tour can be such an indication. A tour with a small filling degree can be a good candidate for a change either by adding orders and then increasing the filling degree or else by removing orders for possibly emptying the whole tour. Another possibility to speed up the search is not to make a complete calculation of the objective value of the possible solutions, but only perform this on the solutions that look promising for being best so far in the search. This requires however a good way of comparing different solution to each other without calculating the objective value.

Our heuristic considers only the movement of single orders, but an improvement of the heuristic could consider making moves of clusters of nodes or complete subtours. We have also focused on a standardized vehicle fleet of similarly sized vehicles. In the real life a heterogeneous fleet where the vehicle size is adjusted to the tour it serves might be equally good. Introducing the time-dimension for a tour and take into consideration the time used for ferries, driving, refilling, coupling and uncoupling the trailer, will make the problem more like the real-world case. It might however increase the calculation time and make it even more difficult to find good solutions.

Another possibility to improve the solution quality is to construct routes where the trailer is acting as a mobile depot even for other vehicles than the one that parked it as suggested by Drexler (2006). Other trucks can stop and transfer milk to the trailer tank when the trailer is parked and yet another truck can drive it back to the depot.

## **Acknowledgements**

The authors want to thank John Alan Haugen at TINE BA region Midt-Norge for providing us with data for this project and explaining us the details of the problem.

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## Appendix A – The final algorithm

The final algorithm for the search is described the following way

**Step 1.** *Create an initial solution  $\sigma$  by running the make-initial-solution algorithm described in Appendix B. Set the best found solution  $\sigma^* = \sigma$ .*

**Step 2.** *Repeat the following tabu search iteration the number of times decided in Section 4.1.3.*

1. *Calculate which tours in  $\sigma$  that are in the part of the neighborhood that should be examined in the current iteration.*
2. *Run through all the tours found in 1.*
  - a. *Select the order  $s$  in each tour with the lowest value of  $\xi(s)$  that is not defined as tabu. If several orders have the same value of  $\xi(s)$  pick one order randomly among those. If all orders are tabu, ignore the tabu criterion.*
  - b. *Update the move counter  $\tau(s)$  used for diversification.*
  - c. *Evaluate the possible moves.*
    - i. *Try to move  $s$  from its current tour  $t_s$  to another tour  $t_{s'}$  which contains a neighboring order.*
      - A. *Insert  $s$  next to the nearest order in  $t_{s'}$ .*
      - B. *Try to improve the solution by running a short local search by moving the last order in the changed subtour in  $t_{s'}$  to other subtours.*
      - C. *If profitable, change parking place for the subtour.*
    - ii. *Try to swap  $s$  from its current tour  $t_s$  with a random order  $s'$  in another tour  $t_{s'}$  which contains a neighboring order.*
      - A. *Insert  $s$  and  $s'$  next to the nearest order in respectively  $t_{s'}$  and  $t_s$ .*
      - B. *Try to improve the solution by running a short local search by moving the last order in the changed subtours in  $t_{s'}$  and  $t_s$  to other subtours.*
      - C. *If profitable, change parking place for the subtour.*
3. *Let  $\sigma'$  be the best solution found in 2b-i or 2b-ii.*
4. *Move to  $\sigma'$ , set  $\sigma := \sigma'$ .*
5. *Update the tabu tenures of the attributes of  $\sigma'$ .*

6. *Update the penalty factor according to feasible or infeasible solution.*
7. *If  $\sigma$  is the best solution found so far, set  $\sigma^* := \sigma$ .*

**Step 3.** *Try to optimize each tour in  $\sigma^*$  by moving orders to other subtours and replacing parking places if favourable.*

**Step 4.** *Report  $\sigma^*$  and stop.*

## **Appendix B – *make-initial-solution* algorithm**

The algorithm for making initial solutions is described as follows

- Step 1.** *Compute the number of tours necessary with reference to the available vehicle fleet, the visiting frequency and the needed supplies for each depot.*
- Step 2.** *Compute the number of seed orders to be selected from each of the original tours used by TINE BA.*
- Step 3.** *Select the seed orders.*
1. *Loop through the original tours and distribute the seed orders to the new tours*
    - a. *Select the order furthest away from the depot as the first seed order.*
    - b. *If two seed orders are needed, select the order with the largest total distance from the first seed order and the depot as the second seed order.*
    - c. *If more than two seed orders are needed, select the next seed order as the one with largest total distance from the previously selected seed orders.*
    - d. *Repeat c until the necessary number of seed orders is selected.*
- Step 4.** *Distribute the orders to the new tours.*
1. *Loop through all the orders not selected as seed orders.*
    - a. *Find the seed order with shortest distance to the order and add the order to the tour containing that seed order.*
  2. *Loop through all new tours.*
    - a. *If a tour is infeasible regarding to the total weight or volume remove the orders furthest away from the seed order until the tour is feasible.*
    - b. *Insert the orders removed in a to the tour containing the nearest seed order among the tours that still has free capacity.*
- Step 5.** *Try to improve each of the new tours as a TSP using a local search with a 2-opt neighborhood.*
- Step 6.** *Loop through the orders in each tour and insert parking places for the tours that are served with a truck and trailer.*

1. *The first parking place is inserted between the depot and the first order. The parking place that has the shortest total distance from these two points is selected.*
  2. *Loop through all orders in the tour and add the amount of each order to the truckload.*
    - a. *When the truck capacity is exceeded or a bottleneck is passed, insert the previously selected parking place before the current order. Then find the nearest parking place between the depot and the current order and insert it before the order. (This parking place can be the same as the previous)*
  3. *When all orders are visited, insert the last selected parking place before returning to the depot.*
- Step 7.** *Try to improve each of the subtours as a TSP using a local search with a 2-opt neighborhood.*
- Step 8.** *Try to improve each tour by moving orders to other subtours.*
- Step 9.** *Loop through all tours and subtours and check other possible parking places. Find the total distance between the other parking places and the first and the last order on the subtour and add this to the distance to the parking place for the next subtour (or back to the depot if the subtour is the last on the tour). If another parking place has less total distance than the current, it should be replaced.*





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