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OPTIMIZATION OF WOOD TRANSPORTATION

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Abstract. The planning of wood supply to pulp and saw mills at Stora Enso in Finland involves multiple optimization models, of which we discuss the short-term transportation models. The inputs to the optimization models are harvest plans on the supply side and mill production plans on the demand side. The overall goal is to transport thousands of batches of timber to dozens of mills as cost-effectively as possible. The planning proceeds in stages: First, harvested batches of timber are combined into units of truckloads. Second, the truckloads are assigned to truck, rail or water transport to mills. Finally, truck routes are planned and scheduled in order to arrange the deliveries of the truckloads.

The three optimization problems are combinatorial in nature and are addressed by heuristic tabu search and mixed-integer linear programming. We give an overview of the models and our solution approaches, and discuss experiences from production use.

Keywords: wood supply, logistics, optimization, tabu search

1 Introduction

The Finnish wood supply business unit of Stora Enso, an international paper, packaging and forest products company, manages a fleet of hundreds of trucks to deliver timber to dozens of paper mills, pulp mills and sawmills, including some external customers. The task of planning and scheduling the truck transport operations has been computer-aided since the 1990's (Linnainmaa et al. [5]). In this paper, we discuss the optimization models of the second-generation truck transport planning system, as implemented by VTT on subcontract to Tieto, an IT service provider.

The primary transportation mode is by truck directly to mills. Rail and water transport have to be arranged a month or more in advance, and thus in short-term truck transport planning they are treated as simple delivery demands at railway stations and ports. We refer to mills, railway stations and ports as *destinations.* All delivery demands at destinations are derived from daily mill production schedules and specified as inputs to the transport planning process.

The short-term planning of the domestic timber transport operation is carried out in units of truckloads (*loads* in brief), corresponding to the capacity of a typical log truck. All harvested timber is assigned into loads, splitting large batches and combining smaller ones together as needed. Loads are first designed on the basis of a harvest plan, and then updated as the exact harvested amounts become known. Loads may also be rearranged later if more timber is harvested nearby, but apart from that a designated load is treated as a single unit until delivery to a mill. The planning of loads involves managers with local knowledge and the load collection model described in section 2.

Every few days, transport coordinators do 1) rough transport planning where all available loads are assigned to destinations and 2) detailed truck routing and scheduling. The assignment of loads to destinations in the first stage covers a period of a few weeks in a rolling horizon fashion and relies on the optimization model described in section 3. Truck routing and scheduling is performed for one period at a time with the aid of the route optimization model discussed in section 4; the optimization only provides a starting point for transport coordinators who update the transport plans on a continuous basis.

Related work is discussed in section 5 and implementation experiences in section 6.

2 Load collection optimization

Truckloads are planned for relatively limited areas by local managers. Harvested timber is classified into *assortments* by species and whether it is pulpwood or saw timber. As a rule, different assortments are not carried in the same load, although exceptions can be made in manual planning. Since different assortments are piled separately, the collection of different assortments can be optimized independently of each other.

In the optimization a batch is specified by location, assortment and the amount of timber (in metric tons). Harvest plans limit feasible destination mills not only by designating the assortment, but also through other timber properties such as diameter and length. In transportation planning each batch is thus already associated with a set of possible destinations. Each batch also has a set of possible collection dates, indicating planned future harvest, a transport deadline, or possible access limitations.

A load is specified by an ordered set of batches and the amounts to be collected. Formally, a solution to the load collection problem is represented by a set of loads, each load specified by an array of pairs (b, a), where b identifies an element from the set of all batches and $a \geq 0$ is the amount collected from the batch (in metric tons). A load is considered a full truckload if its total weight is within a certain narrow range.

2.1 Objective function

The objective of load planning is to create full truckloads which can be collected as fast as possible, within a number of implementation constraints. The objective function is computed by adding penalty factors to the total collection time of the defined loads.

The total collection time is computed in two components: loading time and driving time. The loading time at each batch is assumed constant (in effect penalizing the number of separate batch visits), and the driving time is computed along the fastest route in the road network, using an average driving speed for each road class. In order to leave the truck in a good position to deliver the load, we include driving time from the last batch of the load up to the closest possible destination (one that is in the possible destination sets of all the batches included). Since forest roads can have weight limits, we precompute the driving times between significant locations for three different weight classes, and then take the current load weight into account in all driving time computations.

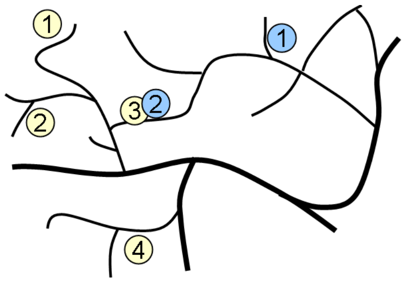

Figure 1. An example of two loads collected respectively from four and two batches in the indicated order. The narrow lines represent forest roads. The two-batch load has to be collected first, so that the collection of the four-batch load can proceed from its third to its fourth batch.

There are two major soft constraints incorporated in the objective function: First, not all timber is required to be assigned to a load, but instead a penalty proportional to the amount of timber outside loads is computed. Second, loads smaller than a full truckload are accepted but a fixed penalty is computed for each. The penalty for a short load is doubled if the load includes a batch marked as requiring urgent delivery.

In order to allow more flexibility in later planning and implementation stages, it is preferable that all the batches included in a load should be close together. In the objective function this is implemented as a penalty as follows: given a load l comprising the set of batches B, the penalty is proportional to $\sum_{b \in B} \sum_{c \in B, c \neq b} r_b(c)/|B|$, where $r_b(c)$ be the rank of batch c in the list of nearest neighbours of batch b.

The most cumbersome batches can only be reached by the truck tractor after detaching the trailer. In this case the collection time is increased by an estimate of the detaching time. After filling up the truck tractor on the batch, it is possible to either transfer the tractor load to the trailer and take the tractor back for more, or to simply proceed to fill the trailer from other batches at better locations. The latter is more efficient; the former is penalized through the addition of extra collection time (representing the additional time required to transfer the tractor load and fetch another tractorful).

2.2 Constraints

The most basic constraints govern the maximum total collection distance and the maximum distance and driving time between two consecutive batches in a load. By adjusting these constraints the users can guide the optimization towards loads they consider appropriate for the region. The possible destination sets of the batches induce the constraint that every load should have at least one common destination. Similarly, every load should have at least one common collection date.

The following constraint is dictated by the fact that trucks cannot accurately measure their loads: a truck should either clear the entire batch, or fill up the truck. It follows that if a batch is split between multiple loads, the batch is last on every load except at most one. In route optimization, the one exceptional load cannot be collected before every other load on the batch has been collected (see also Figure 1).

Often batches can only be reached slowly through low-quality forest roads and the difficulty of reaching batches increases as the truck is weighed down by load. Such forest roads are considered a special road class in the road network data, and for optimization purposes we compute for each batch the distance to the closest "proper" non-forest road.

The basic rule for collecting timber from forest roads is that one should start as far in the forest as possible and proceed towards good roads. We implement the rule by requiring that any consecutive batches that are located on forest roads should be collected in order of decreasing distance to proper road. Once the truck has reached a proper road, it is allowed to return to forest roads, but only up to a given maximum distance. Batches further away than the distance limit thus have to be among the first batches of a load.

Load collection is planned on the basis of harvest plans and data on already harvested timber. Since there is some uncertainty in the planned harvest amounts, it is not easy to tell in advance if a truck would be about to fill up. To improve the chances of the loads being practically implementable, we never put a batch that is still being harvested earlier in the same load than a completely harvested batch.

2.3 Solution approach

The load collection model is addressed by the tabu search heuristic [1], which is essentially local search that avoids getting stuck at a local optimum with the aid of a *tabu list* of solution features. In our implementation the tabu list temporarily prevents batches from either being returned to loads from which they were removed, or to be removed from loads into which they were added.

Before beginning the search, full truckloads are created from the largest batches and then fixed, leaving at most three loads worth of timber unassigned at each batch. The initial solution consists of any previously planned loads on the planning area.

The local search is based on the following operations: *Create* an entirely new load collecting a single batch; *Add* a new batch to any position in a load; *Relocate* a batch from one load to any position in another load; *Remove* a batch from a load; *Join* two loads together, inserting the entire sequence of batches of one load between two batch visits of another (or at the beginning or the end of the other load); *Reorder* the batches in a load using a travelling salesman solver with side constraints.

All operations adjust the amounts loaded from batches to respect the rule that one either clears the entire batch or fills up the truck.

3 Load assignment optimization

In the load assignment stage a rough truck transport plan is designed for the entire country for a period of a few weeks. To be precise, a feasible solution to the load assignment problem specifies for each load a destination and a date of delivery. Only the destination choices at this stage are significant; the date choices are used only when fixing the amounts of different assortments that should be delivered daily.

The objective is to minimize the sum of transport costs and penalties computed for deviations from destination demands and organizational quotas. Transport costs are computed on the basis of actual distances and average transport operator contract rates.

Destination demands are derived from mill production schedules at a daily level. Specifically, a *delivery program* gives for a specific date and a destination the minimum number of loads to deliver and a penalty coefficient for loads missing from the minimum. For each assortment that the production process can use, the minimum and maximum

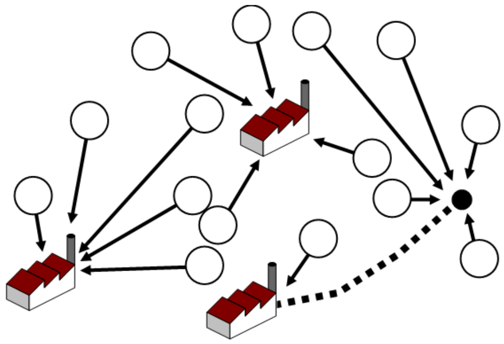

Figure 2. An example of a load assignment with 15 loads assigned to four separate destinations: three mills and one railway station (represented by a black spot).

acceptable number of loads is given as a percentage of the total daily demand. A penalty cost is computed for each load missing from the minimum or above the maximum.

Short-term planning is constrained by *organizational quotas* derived from long-term harvest and transport plans. In load assignment optimization, the most relevant organizational quotas specify for the largest mills the minimum and maximum number of loads of each assortment to be delivered from each of four regions. A penalty cost is computed for each load missing from the minimum, and for each load above the maximum. The quotas are separate for the next route planning period (the next few days), and for the rest of the planning period. Both the organizational quotas and the delivery programs on the route planning period are given priority through higher penalty coefficients. In any case, delivery programs are considered the primary goals, and their penalty coefficients are set high enough to allow deviations from the organizational quotas when necessary.

The load assignment is constrained by the feasible transport dates of the loads, as derived from the possible collection dates of the batches included in the loads. The feasible destination sets of the loads similarly limit the assignment; in case of deliveries to railways stations and ports the final destination of the planned train or ship is considered.

3.1 Mixed-integer model

The load assignment can be solved as a general mixed-integer linear program, specified as follows. Let L denote the set of transportable loads and P the set of delivery programs. The integer decision variables $x_{lp} \in \{0,1\}$, $l \in L$, $p \in P$, specify whether load l is transported to delivery program p. Whenever a delivery is disallowed (e.g. the first feasible transport date of load l is after the date of delivery program p), x_{lp} is fixed at 0.

The overall delivery program goals, assortment-level goals and organizational quotas are all specified as generic delivery goals as follows. Denoting the set of all delivery goals by Γ, the loads that count for goal $g \in \Gamma$ are denoted by $L(g) \subseteq L$ and the delivery programs that count are denoted by $P(g) \subseteq P$. For an overall goal of a delivery program we have $L(g) = L$ and for an assortment-level goal of a delivery program $L(g)$ is the set of all loads of a specific assortment; in either case $P(g)$ is a singleton set. For an organizational quota $L(g)$ contains only the loads in the specific organizational region and $P(g)$ contains all delivery programs of a mill within a period, including those delivery programs at other destinations that represent incoming trains and ships.

Denoting the minimum number of loads in a delivery goal g by $G^-(g)$ and the maximum number by $G^+(g)$, the delivery goal is specified by the constraints

$$\sum_{l \in L(g)} \sum_{p \in P(g)} x_{lp} \geq G^-(g) - u^-(g) \quad \text{and} \tag{1}$$

$$\sum_{l \in L(g)} \sum_{p \in P(g)} x_{lp} \leq G^+(g) + u^+(g), \tag{2}$$

where the variable $u^-(g) \geq 0$ represents the number of loads missing from the minimum and $u^+(g) \geq 0$ represents the number of loads in excess of the maximum.

Every load is required to be transported by constraints of the form

$$\sum_{p \in P} x_{lp} = 1 \quad \text{for all } l \in L. \tag{3}$$

Finally, the objective function is specified as

$$\sum_{l \in L} \sum_{p \in P} c_{lp} x_{lp} + \sum_{g \in \Gamma} \left(c^-(g)u^-(g) + c^+(g)u^+(g)\right), \tag{4}$$

where c_{lp} is the transport cost of load l to delivery program p including possible rail and water transport costs, and $c^-(g)$ and $c^+(g)$ are the delivery goal specific penalty costs for falling short of the minimum number of loads, and exceeding the maximum.

4 Truck route optimization

In route optimization detailed truck routes are planned and scheduled for the entire country for a period of a few days at a time. A feasible solution specifies for each truck the time and location of every load collection, delivery or other stop within the planning period at a resolution of one minute (of course the plans are not implemented quite so precisely). While the destination of each load is fixed, there is a choice of which loads to deliver within the planning period, to which delivery programs. In general, any truck can deliver any load to any destination, but it is also possible for transport coordinators to assign loads to specific groups of trucks, or to limit trucks to specific destinations.

Some trucks are operated by one-man companies, requiring regular rest periods, while others are run by large subcontractors that employ multiple drivers for each truck. In the model, each truck has a set of *driver change points* in the area where the trucking company is based, and a minimum rest time that must be spent at a driver change point between work shifts. The length of a single work shift, i.e. the time between leaving a driver change point and entering one again, is limited by a maximum value. Drivers are not identified in the model, nor are their individual work schedules considered; we simply require each truck to visit a driver change point regularly.

Truck routes can be formally defined as paths on a directed graph with six kinds of nodes: a *start node* for the location of each truck at the time it is first available on the planning period, a *collection node* for every load, a *delivery node* for each feasible pair of a load and a delivery program, a *crane pick-up node* for every batch (see section 4.3), a number of *driver change nodes* for each pair of a truck and a driver change point, and a *stoppage node* for every planned truck stoppage time and location (section 4.3). A route schedule is defined by associating a start time with each node on the route.

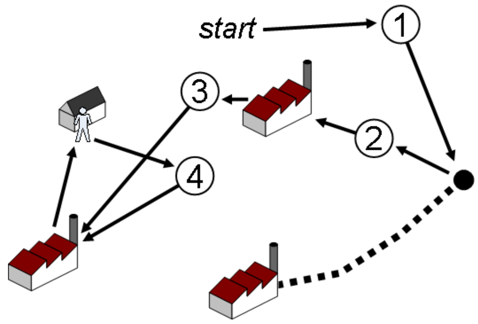

Figure 3. A simplified diagram of a route with deliveries of four loads (numbered) to three destinations and a driver change between the deliveries of the third and the fourth load.

Nominal driving times between all nodes are computed in advance for three different truck weights (empty, half-full or full) along the fastest route in the road network. Driving times as well as loading and unloading times are adjusted by separate truck speed parameters for the varying performance levels of individual trucks and their drivers.

4.1 Constraints on deliveries

Compared to load assignment optimization, the daily delivery programs are specified in more detail: First, different assortments are now given separate delivery programs with the minimum and maximum number of loads derived from the delivery plans of the load assignment stage. Second, while the delivery programs and the number of deliveries are still nominally specified for an entire day, allowable delivery times within the day are specified as a set of time windows (intervals) at a resolution of one minute.

For delivery programs that represent the loading of a train or a ship, a single time window usually suffices to specify the loading hours. For delivery programs at pulp and paper mills, time windows are derived from the exact schedule of the production process—the goal is that loads are delivered directly to the process, without intermediate storage or handling at the mill yard. In practice, variations in delivery schedules are compensated with local buffer storage at the mill yards. To avoid congestion at the weighing and unloading points at destinations, a minimum permissible time between two consecutive deliveries is also defined for each delivery program.

4.2 Load collection

The possible collection times of a load are specified as a set of time windows at a resolution of one minute. In practice this level of precision is relevant only seasonally, when the terrain freezes solid by night and thaws into undrivable condition by day; otherwise the collection times are specified at date level as in the earlier planning stages.

Passing another truck on forest roads can be difficult or impossible. Hence each batch location is given a minimum permissible time between two consecutive truck arrivals. However, we do not allow waiting between visits to two batches of the same load—the arrival time at each individual batch is computed at a constant (or rather, truck dependent) offset from the scheduled start time of the load collection node.

As noted in section 2.2, when a batch is split between multiple loads, one of the loads may have to be collected later than the others. We treat these cases as strict constraints on the start times of the load collection nodes, adjusting by the times it takes to reach the batch from the start of each load collection.

4.3 Other stops

Log trucks carry a small crane with them for unassisted loading and unloading, but more efficient cranes are available at mills. When delivering multiple near-by loads by the same truck, it is usually more cost-effective to leave the crane in the forest than to carry it all the way to the mill and back. In the model detaching the crane takes a fixed time at the last batch of a load, and then requires another visit to the batch (a crane pick-up node) between the delivery of the load and the collection of the next load.

By default, driver changes can be scheduled at any time of day. Especially for trucks operated by one man, a more rigid schedule with nights off may be preferred. To reserve nights or entire days off, each truck can be given any number of stoppages with a fixed start time and duration. All stoppages are assumed to involve a driver change. There is an option to disallow carrying a load over the duration of a stoppage.

Driver changes and stoppages are associated with a set of alternative locations so as to minimize the diversion from the truck route: in practice the fresh driver takes a car to the chosen driver change point and then switches vehicles with the outgoing driver.

The trucks may already have other work, and become available for the route optimization at any place and time during the planning period. A start node specifies the time and the place, and an artificial stoppage node specifies the last known driver change. A route is finished off by a driver change after the end of the planning period.

4.4 Objective function

The objective includes transport costs and a number of artificial penalty factors. Transport costs are nonlinear in distance and given only as look-up tables. The actual rates for truck transport are based on the shortest possible distances between batches and destinations, ignoring driver changes and stoppages entirely. The rates are artificially discounted whenever the crane is left behind. To keep the routes implementable, whenever driver changes or stoppages are ignored in a batch-destination distance, a penalty proportional to the square of the missing distance is added to the objective.

As in load assignment, deviations from delivery program goals and organizational quotas result in a fixed penalty for each load missing from the minimum or each load in excess of the maximum. Overall organizational quotas, which are not restricted to any particular destination, become significant constraints in route optimization: without them some smaller areas could end up with no work at all for the planning period. To encourage fair distribution of work, it is also possible to specify a quota for each truck (in tonne-kilometres), with a penalty proportional to the shortfall.

Two penalty factors discourage uneven work shifts: First, a waiting penalty is computed for any time trucks spend idle in the middle of a shift, i.e. between load collection, delivery and crane pick-up visits. Second, in order to increase the average amount of work per shift, a constant shift starting cost is computed every time a truck leaves a driver change to collect or deliver a load or to pick up its crane.

Loads can be marked as requiring local knowledge, in which case collecting the load by a truck from another region incurs a penalty.

There are two soft constraints incorporated in the objective function, with penalty coefficients that increase regularly: the maximum work shift length, and the requirement to deliver loads if the last possible collection date is on the planning period.

4.5 Solution approach

As in the load collection model, we employ the tabu search metaheuristic. The tabu list temporarily prevents a load from appearing on a truck from which it was removed, and from being removed from a truck on which it was inserted. The initial solution includes for each truck a start node, any specified stoppages, and as many driver changes as necessary to create feasible work shifts. We run the search in two phases: In the construction phase the routes are repeatedly filled in, then the penalty factors are randomly perturbed and the search is restarted from the initial solution. In the improvement phase longer search runs are performed, and restarts clear only 10 % of the routes.

The local search is based on the following operations: *Insert* a load collection and its delivery on a route, choosing the best delivery program and collection and delivery times; *Drop* a load collection and its delivery from a route; *Move* a load collection and its delivery from one route to another, optionally switching to another delivery program in the same destination; *Switch* a load and its delivery on a route to another load and delivery, choosing the best delivery program and collection and delivery times; *Exchange* a driver change with an adjacent collection or delivery on a route.

Insert operations are only allowed on every fourth iteration, as per [2]. Routes are regularly improved by a dynamic programming algorithm that selects optimal start times for nodes and when to detach the crane, without modifying the routes otherwise.

5 Related work

Compared to standard vehicle routing problems [7], wood transportation is challenging due to complex constraints and the large scale of the operations.

Weintraub et al. [8] describe a pioneering routing and scheduling system for log trucks and cranes, based on heuristic decision rules. Palmgren [6] presents a solution based on column generation and near-exact heuristics to a single model that covers essentially the same issues as our three separate models; the solved instance sizes are however limited. Gronalt and Hirsch [4] develop a tabu search algorithm for routing full truckloads with time windows. Flisberg et al. [3] handle instances closer to the sizes met at Stora Enso, using a two-stage solution where they first create truckloads bound to destinations by linear programming based heuristics, and then treat the problem as a vehicle routing problem with time windows and use tabu search.

6 Experiences

The load optimization model is used by local procurement managers who are familiar with the terrain and can improve the computer-designed loads as needed, in order to make them easier to collect in practice. The load assignment model and the route optimization model are used by transport coordinators; the former is simple enough that results of computer optimization are usually accepted as is, while the latter is complicated enough that the heuristic computer solution can often be improved manually.

While the heuristic search algorithms do provide high quality solutions faster than a human could, the solutions can change in an unpredictable manner with even small changes in input data. Together with the nontrivial nature of sensitivity analysis in combinatorial optimization, this makes it difficult to determine values for the penalty cost coefficients and other model parameters. Extensive testing was required to select satisfactory parameter values for production use.

Of the three optimization stages, load optimization typically converges in minutes as the planning task is geographically limited, and the load assignment model is simple enough that it is also solved in minutes. Route optimization over the entire country however takes hours to find a good solution.

As the system has been in operational use since 2002 and the business environment has evolved, the short-term transport planning process has changed relatively little. There have been changes in the optimization model specifications, and for the most part new penalty factors and constraints have been easy to implement. However, the complexity of the ad-hoc algorithms processing truck schedule constraints has hindered updates. Along the way, some initially specified model features have fallen out of use: for example, the full load assignment model includes costs and constraints related to harvest planning, beyond those described in section 3.

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