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A bi-level decision model for timber transport planning

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Abstract. We propose a decision model to optimize the transport of wood from the forest, based, first, on the elaboration of a multi-period multi-product tactical plan of aggregated activities to assess the global capacities required. The tactical plan is then refined into daily routing plans to minimize the global distance travelled by a truck fleet. Benchmarking our decision model with an industrial case in the Aquitaine region has shown a significant performance improvement.

Keywords: Forestry logistics, wood supply, tactical planning, routing optimization

1 Introduction

This paper addresses the specific problem of timber transport from the forest to the clients, e.g. sawmills, paper mills. Section 2 highlights some specificities of the wood sector regarding the actors and the processes involved in transport activities, then reviews the literature on wood transport management. Our decision model to plan timber transport is detailed in Section 3, whereas Section 4 is devoted to the benchmarking of our results with an industrial case.

2 Challenges of wood transport

2.1 Ecosystem of the wood supply chain

Sourcing and transporting timber from the forest to the transformation sites involves several processes which may variably be internalized or outsourced by the actors. In the typical configuration shown in Fig. 1, the processes are orchestrated by a Forest Operator who purchases standing timbers from Forest Owners. The Forest Operator has a panel of clients (e.g. Sawmills) to supply from any appropriate source. Each physical operation is usually subcontracted: harvesting (including felling, delimbing, and primary transport) to Loggers, transport to Haulers.

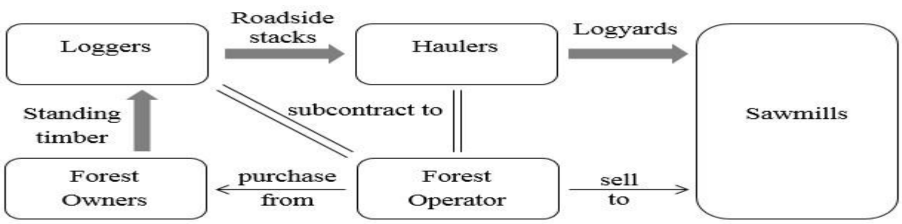

Figure 1: Actors of the wood Supply Chain

Further details on the forestry process are given in [1]. Other configurations are also frequently encountered, in which some of the actors have internalized some or all of the processes. For instance, a transport company may have integrated the wood

purchase & sale transactions; alternatively, a client-factory may carry-out its own transport operations of wood bought to Loggers [2].
In many cases, the relationships between the actors are of the peer-to-peer type. Nevertheless, as in many other industrial sectors, the search for productivity improvement nudges the players to form collaborative Supply-Chains [3], to improve market responsiveness, share financial risks, achieve economies of scale and make an efficient use of finite resources. The structuration of the wood supply chain into collaborative organizations has seen increasing exposure in the scientific literature. Examples include an overall mapping of the value chain was carried out in the FP7 project FLEXWOOD. In Aquitaine, a series of projects [4] have developed computer-aided decision tools to facilitate transport planning. In the province of Quebec, Canada, further to research results on wood supply chain collaborative management [5], the VTM (Virtual Transportation Manager) tool was elaborated to optimize a fleet of trucks by means of geolocalisation and internet.

2.2 Transport planning

It is commonly admitted that a main factor of wood supply cost is transport. This paper focuses on the transport process stricto sensu. The products to be transported are piled besides forest roads in homogeneous stacks, according to wood species, quality, diameter and length [6]. The timber transport may be formalized as a Capacitated Vehicle Routing Problem (CVRP) to be solved with an objective of cost minimization [7]. Some of the constraints to cope with are not specific to the wood sector: the availability of products to load, the limited capacities of trucks, the delivery time windows are generic constraints in most of the transport optimization problems. Nevertheless, the timber transport problem has also some particularities, among which we emphasize:

- ✓ the scalability of the network, as loading sectors permanently change once logging sites have been exhausted. In case of small forest owners, like in the Aquitaine region where the forest is mainly private, the volume of wood drawn from each cut blocks (logging sites) is small and the loading points change frequently,

- ✓ the need for emptying roadside stacks; as the volume of wood in roadside stacks is obviously not an integer multiple of the capacity of trucks, it is necessary to organize *collection runs* to empty stack bottoms which are all the more frequent as stack sizes are small,

- ✓ the tremendous latitude to take the wood from whatever loading location, as long as the quality of the wood fits clients' requirements.

Moreover, the transport of wood is subject to specific national and regional regulations which stipulate the loading weight of trucks and the authorized roads [7].

The decisions subject to optimization are of two types:

- ✓ allocating sources to clients : the decision to load the wood (where, how much, when) in specific loading points in order to deliver the appropriate amount of wood expected by each client. The challenge here is to find an allocation that minimizes the global displacement of wood.

- ✓ editing the routes and instructions to each truck driver, in conformity with work regulation, authorized roads and delivery hours. The challenge here is to schedule the transports, so that the unloaded distance is globally minimal by finding out *backhauling* routes when possible.

Optimization models using Mixed Linear Programming or heuristics are available in the literature [8]. FP7 Project FOCUS has promoted the combination of simulation and optimization techniques to mix the predictive and adaptive modes of wood transport. In practice, the use of routing optimization software is not commonly used by transporters, due both to their cost, complexity, and to their limited capability of producing schedules in an acceptable time.

The research reported in this paper is oriented towards two objectives. First, to dissociate and interrelate decision making at the tactical level and at the operational level. At the tactical level, the area of questioning is on the elaboration of a global workload plan for the mid-term (one to several weeks), as well as on the evaluation of the transport capacities required. On this basis, the issue is to be able to reserve transport capacities required by the plan. In case of under-capacity, to subcontract additional capacities or, in case of over-capacity, to estimate which internal transport capacities might be allocated to further activities. Second, turn the tactical workplan into daily routing optimization problems to be solved at the operational level to find out intelligent routes and efficient loading/delivery scheduling.

3 Model

3.1 Tactical planning

The decision model sets up a multiperiod plan defining an allocation of supply points to delivery points and the associated amounts of wood to load and deliver. The global demand per client and per product is given, as well as the initial level of roadside log piles per product. The point to point road distance matrix and the aggregate capacity of transport per period are supposedly known. The eventual regeneration of log piles during the transport plan is taken into consideration. We minimize a compound objective function compromising between the global displacement of wood, the emptying of residual piles and an optimization policy (activity balancing vs makespan shortening). The decision model as a Mixed Linear Programming formulation is detailed below:

Sets	
I	Supply sites (roadside stacks)
I^*	Supply sites (roadside stacks to empty)
J	Client sites
S	Network nodes: $S = I \cup I^* \cup J$
Δ	Road distance matrix
H	Planning horizon
P	Product types
Indexes	
i	Roadside stack site : $i \in I \cup I^*$
j	Client site : $j \in J$
p	Product : $p \in P$
h	Planning period: $h \in H$
δ_{ij}	Road distance from site *i* to site *j* : $\Delta = (\delta_{ij} \mid i, j \in S)$
Data	
D_{jp}	Demand of client site *j* for product *p* to deliver over horizon *H,* in ton
$y_{ip}(0)$	Initial stack level for product *p* at supply site *i,* in tons
$b_{ip}(h)$	Amount of product *p* added to stack at site *i* during period *h,* in ton
$X(h)$	Aggregate transport capacity available for period *h*, in ton.km
Decision variables	
$T_{ijp}(h)$	Amount of product *p* to transport from site *i* to site *j* during period *h*

$y_{ip}(h)$ stock level at site i for product p, beginning of period h
f_i binary, set to 0 when stack i is empty at the end of the plan
$\tau(h)$ binary, set to 0 when period h remains unused

Constraints

$$\sum_{i,h} T_{ijp}(h) = D_{jp} \qquad j \in J,\ p \in P \tag{1}$$

$$y_{ip}(h) = y_{ip}(h-1) - \sum_j T_{ij}(h) \qquad i \in I^*,\ p \in P,\ h \in H \tag{2}$$

$$y_{ip}(h) = y_{ip}(h-1) + b_{ip}(h) - \sum_j T_{ij}(h) \quad i \in I, p \in P \quad h \in H \tag{3}$$

$$\sum_{i,j,p} T_{ijp}(h)\delta_{ij} \le X(h) \qquad h \in H \tag{4}$$

$$y_{ip}(H) \le M f_i \le M y_{ip}(H) \quad i \in I^*,\ p \in P \tag{5}$$

Constraints (1) to (4) satisfy demand fulfilment, the follow-up of stack levels over the plan, and the respect of transport capacities. Constraints (5) checks that the stack remainders are emptied during the plan.

Objective function

$$Min\ (\alpha_1 J_1 + a_2 J_2 + a_3 J_3) \quad \text{with} \quad \alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{6}$$

where

$$J_1 = \sum_{i,j,h} T_{ijp}(h)\,\delta_{ij} \tag{7}$$

$$J_2 = \sum_{i \in I^*} f_i \tag{8}$$

$$J_3 = \sum_h \tau(h) \tag{9a}$$

$$J_3 = \sum_h \left| \sum_{i,j,p} \delta_{ij}\ [T_{ijp}(h) - \tfrac{1}{H} \sum_h T_{ijp}(h)] \right| \tag{9b}$$

Weights $\alpha_1, \alpha_2, \alpha_3$ allow to compromise between the minimization of the global displacement of wood (7), the emptying of stack remainders (8) and the minimization of makespan (9a). Alternatively, substitute (9b) with (9a) to balance the activity over the planning horizon. Note that the absolute value in formula (9), here presented as such for simplicity, is in fact linearized in the LP model.

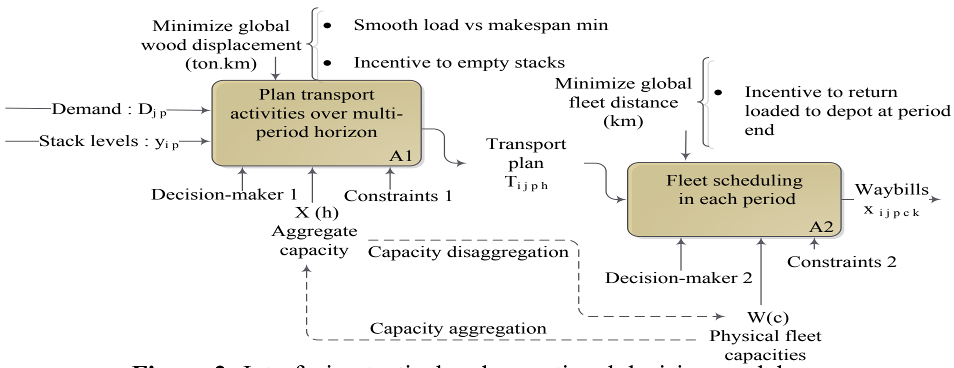

Figure 2: Interfacing tactical and operational decision models

3.2 Routing optimization

The tactical planning model defines the transport activities to be carried out for each period of the plan. At the operational level, the role of the routing optimization model is to organize the execution of transport for each period h of the tactical plan, by determining the operational routes and the movements of a fleet of trucks. Here, we consider the capacity of the physical transport resources, that is, the admissible load of the trucks. Interfacing the tactical and the operational decision model, see Fig. 2, requires to interrelate the operational transport capacity of a pool of trucks with the aggregate transport capacity considered at the tactical level over each period, as follows :

$$X(h) = \rho \sum_c W_c \delta_c(h) \tag{10}$$

with

$X(h)$ aggregate transport capacity of available fleets during period h
W_c capacity of truck c
$\delta_c(h)$ admissible driving distance of truck c over period h
ρ mean load rate of fleet

The relation (10) is the link between the tactical and operational level and should be instantiated carefully, either through statistics on previous activities, or by iterative adjustments. Clearly, overestimating $X(h)$, the aggregated transport capacity by period would lead to tactical plans which are not feasible at the operational level, whereas underestimating $X(h)$ would underexploit the real transport activities.
Note that if the supply basin and the delivery basin are fully distinct, no backhauling is possible and every two movements is unloaded, hence $\rho \leq 0.5$. Should the two basins be overlapping, one can expect some backhauling movements, therefore ρ may overpass 0.5. The value is case-dependent and should be prudently assumed.
The routing optimization model is in charge of scheduling truck movements over one period (typically one day) and determines the amounts of wood to load and deliver at each movement. By optimizing the routes for the whole fleet of trucks in the same time, we expect to reduce the unloaded mileage as far as possible, including any backhauling opportunities. The objective function is the minimization of the total distance travelled by the fleet to execute the daily transport plan. We may also compromise between the minimization of total distance and an incentive to return trucks loaded to their depot at the end of the day in order to spare one movement the next day. The decision model formulated as a Mixed Linear Programming formulation is detailed below :

Sets
C available trucks

Indexes
c truck : $c \in C$
s^* depot site : $s^* \in S$

Data
T_{ijp} amount of product p to transfer from supply site i to client site j
W_c capacity of truck c
K maximal number of movements by truck in the period

Decision variables

For each truck $c \in C$

z_{ijck} binary, set to 1 when movement k is from site $i \in S$ to site $j \in S$
x_{ijpck} amount of product p loaded in site i and destinated to site j by movement k
w_{jpck} on truck amount of product p destinated to site j in movement k

Constraints

$$\sum_{j\in S} z_{s^*jc1} = 1 \qquad c \in C \tag{11a}$$

$$\sum_{i\in S} z_{is^*cK} = 1 \qquad c \in C \tag{11b}$$

$$\sum_{i\in S} z_{isck-1} - \sum_{j\in S} z_{jsck} = 0 \qquad s \in S,\ c \in C \qquad k > 2 \tag{12}$$

$$\sum_{c,k} x_{ijpck} = T_{i\,j\,p} \qquad i \in I,\ j \in J,\ p \in P \tag{13}$$

$$\sum_{j,p} w_{jpck} \leq W_c \qquad c \in C \qquad k \in K \tag{14}$$

$$M \sum_{s\in S} z_{isck-1} \geq x_{ijpck} \qquad i \in I,\ j \in J,\ p \in P,\ c \in C \qquad k > 1 \tag{15}$$

$$M \sum_{i \neq j \in S} z_{isck-1} \geq w_{jpck-1} + \sum_{j \in S} x_{ijpck} - w_{jpck} \geq 0 \qquad k > 2 \tag{16a}$$

$$M(1 - \sum_{i \neq j \in S} z_{ijck-1}) \geq w_{jpck} \geq 0 \qquad j \in J,\ p \in P,\ c \in C \quad k > 2 \tag{16b}$$

Objective function

$$\text{Min } \sum_{i,j,c,k} \delta_{ij}\, z_{ijck} \tag{17}$$

Constraints (11a) and (11b) require that the truck starts from the depot at the beginning of the period and returns to it at the end of the period. Constraint (12) ensures the continuity of the route. Constraint (13) is required to realize the transports intended in the period. Constraint (14) excludes any truck overload. Constraint (15) synchronizes truck's loading and position. Constraints (16a) and (16b) update the truck load at the end of each movement, depending on the delivery and the loading achieved on the arrival site.
The objective function minimizes the global distance travelled of the fleet.

4 Case study

This section reports on an application of the decision models presented above to industrial data provided by a wood transport SME in the Aquitaine region. In the current practice (As-is) of this enterprise, the technical managers daily elaborate the route sheets for the next day. The data provided traces one week of activity of the drivers, showing the daily movements of the trucks and the amounts of wood that were loaded and delivered at each movement. We have observed that, most of the time, the trucks return loaded to the depot, to be preloaded for the day after. From the GPS coordinates of supply and delivery points, we have derived the matrix of road distances Δ by using MapPoint.

Table 1: As-Is operational performance

	Tonnage	Distance km	Wood displacement ton.km	Truck load rate	Global efficiency ton/km
Monday	**407**	**2546**	**52111**	**45%**	**0.16**
Truck 1	74	494	10892	40%	
Truck 2	74	690	12571	40%	
Truck 3	111	395	7533	48%	
Truck 4	74	686	12257	40%	
Truck 5	74	279	8858	50%	
Tuesday	**407**	**2812**	**53842**	**51%**	**0.14**
Wednesday	**407**	**2753**	**52994**	**50%**	**0.15**
Thursday	**481**	**2475**	**43771**	**48%**	**0.19**
Friday	**444**	**2125**	**45257**	**50%**	**0.21**
Global	**2146**	**12710**	**247975**	49%	0.17
Industry wood	1665	11755	228718		
Sawmill wood	481	955	19257		

We have computed the As-Is Performance Indicators (IP), see Table 1. The fleet is made of 5 trucks with capacity 37 tons. Two different types of wood (industry wood, sawmill wood) were transported from 15 sources to 11 destinations. The wood tonnage is the amount of product that was effectively delivered to the clients. The distance travelled includes unladen and laden movements. The wood displacement, in ton.km, refers to laden movements. The truck load rate is the ratio of the embedded load of a truck to its capacity. Last, we compute an efficiency indicator, in ton/km, as the ratio of a global mass of wood delivered to the global distance required. The As-Is PIs are computed by day, by truck, and by truck movement. Focusing on the global values over one working week of activity (Monday to Friday), we observe that the 2146 tons of wood to deliver to fulfill the clients' orders have required a global distance of 12710 km, leading to an efficiency of 0.17 ton delivered by km travelled. The observed mean truck load rate of the fleet is 49%.
Now, consider the same transport problem and apply the data to our bi-level decision model. First, a tactical plan is computed (Table 2) by using the model presented in

section 3.1, so that the global wood displacement is minimal and the load uniformly distributed over the week, according to a load smoothing policy. Additionnally, an incentive to empty roadside stacks is applied. The tactical optimization is made under aggregate capacity constraints, in ton.km, per day. According to relation (10), on the basis of 5 trucks with capacity 37 tons, a load rate of 0.5 and a maximal distance of 500 km a day, our assesment of the daily aggregate capacity is *X*= 46500 ton.km. As a result of the tactical optimization, it can be seen that the 2146 tons to deliver may be distributed over the five days using 70 % of the daily capacity *X,* for a global wood displacement of 162758 ton.km, a much lower effort than the 247975 ton.km observed in the As-Is case. According this result, the overcapacity of the aggregate transport ressource is 30% and might have been spared or allocated to further business.
Last, by using the model presented in section 3.2, let the feasibility of the tactical plan be tested at the operational level, where the routes of each truck are defined taking into account their physical capacity. Each daily transport activity generated by the tactical plan is turned into an itinary for each truck, so that the daily distance travelled by the fleet is minimal. We take 4 trucks the capacity of which is 37 tons each. The routing optimization model has found the solution presented in Table 3, showing that i) 4 trucks are sufficient where 5 were used in the As-Is practice ii) the wood displacement is similar to the one evaluated at the tactical level, iii) the global distance travelled by the fleet is significantly shorter than in the As-Is case, iv) the efficiency of the global delivery amounts 0.20 ton/km instead of 0.17 in the As-Is case. Note that the average truck load in our scenario is lower than in the As-Is case, due to the fact that the optimizer returns empty trucks to the depot at the end of the day.

Table 2: Tactical planning

	Tonnage	Emptied roadside stacks	Wood displacement ton.km	Aggregate load rate	unused aggregate capacity
Monday	**481**	**0**	**32552**	**70%**	**30%**
Industry wood	370	0	28393	61%	
Sawmill wood	111	0	4159	9%	
Tuesday	**333**	**1**	**32552**	**70%**	**30%**
Industry wood	259	0	29900	65%	
Sawmill wood	74	1	2652	6%	
Wednesday	**444**	**1**	**32552**	**70%**	**30%**
Industry wood	407	1	32280	70%	
Sawmill wood	37	0	272	1%	
Thursday	**481**	**0**	**32552**	**70%**	**30%**
Industry wood	222	0	21589	47%	
Sawmill wood	259	0	10963	24%	
Friday	**407**	**0**	**32552**	**70%**	**30%**
Industry wood	407	0	32552	70%	
Sawmill wood	0	0	0	0%	
Global	**2146**	**2**	**162758**	**70%**	**30%**
Industry wood	1665	1	144712	62%	
Sawmill wood	481	1	18046	8%	

Table 3: Optimizing operational transport

	Tonnage	Distance km	Wood displacement ton.km	Mean truck load rate	Global effeciency ton/km
Monday	**481**	**1950**	**32961**	**41%**	**0.25**
Truck 1	148	427	7470	44%	
Truck 2	111	457	8464	43%	
Movement 1	0	19	0,00	0%	
Movement 2	37	95	3539	100%	
Movement 3	0	95	0,00	0%	
Movement 4	37	95	3539	100%	
Movement 5	0	95	0,00	0%	
Movement 6	37	37	1386	100%	
Movement 7	0	18	0,00	0%	
Truck 3	111	453	7300	38%	
Truck 4	111	612	9728	38%	
Tuesday	**333**	**2016**	**33403**	**35%**	**0.17**
Wednesday	**444**	**2366**	**33298**	**40%**	**0.19**
Thursday	**481**	**2288**	**34082**	**41%**	**0.21**

Friday	**407**	**2323**	**32611**	**41%**	**0.18**
Global	**2146**	**10945**	**166355**	**39%**	**0.20**
Industry wood	1665	10072	148301	38%	
Sawmill wood	481	873	18054	46%	

5 Conclusions

Benchmarking the two-level optimization model presented in this paper with a real case application shows that significant performance improvement may be expected from the minimization of wood displacement at the earliest stages of tactical decision making, before trying to optimize the routes at the operational level. The justification of the tactical reasoning is also to implement specific policies such as load smoothing over a set of periods or makespan shortening, and to roughly assess the capacity required to reserve the transportation means for each period of the tactical plan. On this basis, one may have to outsource transports if the internal capacity appears to be unsufficient for some period, or, in case of overcapacity, to assess which additional orders may be added to the plan from further business. Clearly, the tactical transport plan must be validated by proving the feasibility of the operational routes, taking into consideration the constraints of truck capacity, fleet size, maximal travel distance in the period for each truck. Note that a sensitive adjustment of the two-level decision making is the relationship (10) that links the aggregate capacity on the basis of which the tactical optimization is achieved to the physical transport capacity of the fleet.

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