Backhauling in forest transportation - models, methods and practical usage

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Abstract

Transportation planning in forestry is divided into strategic, tactical and operational depending on the length of the planning horizon. We consider a tactical problem of finding efficient backhauling routes. Given a set of supply and demand points the backhauling problem is to identify a set of efficient routes which is a combination of direct tours between supply and demand points such that the unloaded distance is minimized. Given these routes we formulate a linear programming problem where the solution is the actual flows in the routes. The problem normally has a time horizon ranging from one to five weeks. However, in some cases it can be included in strategic planning for more than one year and as a basis for daily operative route planning. The size of the problem increases rapidly with the number of supplies and demands and we describe a column generation approach for its solution. Models and methods have been used with success in a number of case studies and in decision support systems. We describe the model and solution method and report on case studies and systems where the approach has been used.

Keywords:

Transportation, Modelling, Decision Support System, Linear programming, Optimization, Forestry

1 Introduction

The forest industry is very transport intensive. In Sweden it accounts for more than 25% of the total land-based transportation work ([14]). One half, roughly, is attributable to the wood flow (roundwood and chips) and the other half to the distribution of finished products. About 90% of the wood is transported by truck and the rest by rail and ship. The rail volume is also subject to truck transportation from the harvesting area to the reloading station.

The transportation planning is done in several steps and is divided into strategic, tactical and operational planning. This deals with transportation of logs from harvest areas or terminals (supply points) to industries such as paper mills, pulp mills, saw mills, heating plants and terminals (demand points). Decisions on a strategic level is often influenced by harvesting and road building/maintenance considerations for several years. Tactical decisions often concerns planning from one week to one year. On an annual basis transportation is often integrated with harvest scheduling. Here it supports how to combine harvest areas and assortments against industries. This is also used as a basis to distribute areas to own or sub-contracted transport organizations/ hauliers. A problem which often ranges from one to five weeks is to decide the destination of logs, that is, which supply point should deliver to which demand point. This is used to define transport orders for hauliers or transporters. The operational problem is to decide actual routes for individual trucks.

General planning of backhauling, or deciding efficient routes for individual trucks, is usually handled on operative level. It belongs to the area of vehicle routing in which there is a vast literature, see e.g. Desrosiers *et al.* [3]. Fleischmann *et al.* [5] reviews literature specifically dealing with backhauling (or reverse logistics) in operative vehicle routing. Our problem belongs to a tactical level and we will only consider flow and not routes for individual trucks. An early work in this area was Carlsson and Rönnqvist [2]. Since then a system for backhauling has been used by the Forest Research Institute of Sweden (Skogforsk) and used in a number of case studies, see e.g. Forsberg [6, 7]. A decision support system FlowOpt, see Forsberg *et al.* [8], was developed and has been used for logistics planning in several forest companies. In Eriksson and Rönnqvist [4] backhauling is used as an important tool in a web based system to support transport planners in operational routing. In Carlgren *et al.* [1] backhauling is dealt with in a context where the wood allocation is optimized together with sorting policies, i.e. the number of different assortments to divide the wood into during harvesting (bucking). Palander [13] presents a Linear Programming (LP) model in which backhauling opportunities are selected heuristically for inclusion in the LP-formulation. Results are presented from a case study showing significant cost savings.

The aim of this paper is to give a solid background to the backhauling problem. This include the general model and solution methods. We also provide a description of case studies and the development of systems where backhauling is a vital component/part. This with the intention of giving the reader a thorough understanding of how the model performs in realistic cases and an indication of the potential for productivity gains to be achieved through increased use of backhauling in practise.

The outline of the remainder of this paper is as follows. We start by describing backhauling in detail. This includes the cost structure of roundwood truck transports and the savings resulting from reduced empty driving. Thereafter we develop the model and present a small example for illustration purposes. In Section 5 we describe the solution methods. In Section 6 we describe case studies and in Section 7 practical implementations. Then follows a discussion about implementation and practical issues, and finally we make some concluding remarks.

2 The Problem

Trucks used for roundwood haulage are specialized for the purpose e.g. by having their own crane, see Figure 1. They are used for carrying saw or pulplogs to an industry (saw, pulp or paper mill). Very rarely will there be any cargo for these vehicles to load directly at the industry. Instead they will have to cover an empty distance to a harvest area, where another load is picked up. If the truck is returned to the initial pick-up area for another load to the same industry, the load fulfilment will become just 50% (or probably less if the empty driving to the first pick-up point, and from the last delivery point, for the day, is included).

Figure 1: A truck specialized for roundwood haulage. In this case with its own crane loading and unloading

A key to achieve higher efficiency is to find cargo that is going in opposite directions whereby it will be possible for a truck to travel loaded in both directions. The empty driving can be reduced if the truck is directed to a harvest area near the delivery point to pick up wood which is due for delivery to an industry near the initial pick-up point. Since the wood assortments (saw and pulplogs etc.) at a harvest area normally are transported to different industries, such combinations of trips can often be found. The number of possible combinations will be affected by how the wood at harvest areas is allocated to different industries.

We begin the problem formulation by investigating the cost structure. A haulage task is defined by its origin, i, and destination, j. Moreover, it is also based on assortment because of different species, density and dimensions. At each harvest area there are generally several assortments (typically 5-15) in different piles. To deal with this we will make use of the notation supply point which is a combination of a geographical location and an assortment. At industries there may be demand of several assortment or combination of assortments (assortment groups). In the same way we define a demand point as a combination of industry and assortment group. Possible combinations of supply and demand points will be considered explicit by forming sets of possible combinations. We assume there are m supply points and n demand points. We will use the sets I and J to define the points i.e. $I = \{1, 2, \ldots, m\}$ and $J = \{1, 2, \ldots, n\}$. If the haulage task is carried out in a traditional way, by a truck going back and forth, we denote it a *direct tour*, k. We define the set R^d of all direct tours as $[i, j] \in R^d$ $(i \in I, j \in J)$.

Wood haulage by truck is generally paid according to a price formula having the form, $c_k^d = \alpha + \beta d(k)$. Here c_k^d is the direct haulage price per tonne between the supply-demand pair $[i, j]^k$of tour k and $d(k)$ the corresponding one-way distance. The parameter α is a fixed cost, covering e.g. loading and unloading, whereas β is related to variable time and distance dependent costs such as e.g. labour and fuel. In cases where this formula is not used, prices are instead agreed for specific haulage distances (e.g. 20 km, 50 km 100 km etc.), and interpolated between these for all other distances. In most cases these prices are also completely linear and can thus be converted into the above formula. Empty driving is usually not compensated specifically. The haulage rate is based on the assumption that the driver returns to the pick-up location, i, for another load. Should there be a possibility of combining the haulage task with another haulage task (i.e. a backhaulage as shown in Figure 2) to reduce empty driving, there is normally a rebate agreed to be deducted from the gross price.

We denote the combined route a *backhaul route* and the rebate ρ per tonne and distance unit. The commercial benefit of the route for the transport buyer is equal to ρ and the gross commercial benefit for the haulier can be expressed as $\beta - \rho$. To get the net profit for the haulier, we will have to deduct the extra costs of driving loaded versus unloaded,

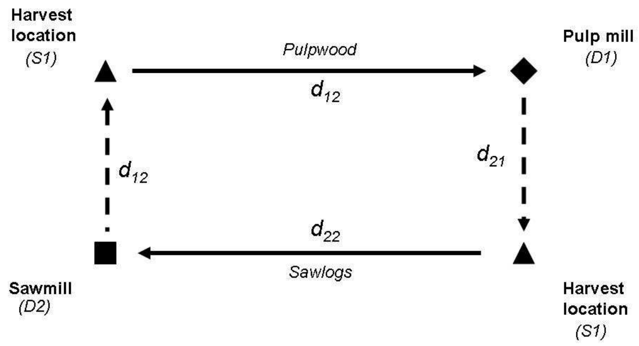

Figure 2: An illustration of a backhaulage route constructed by two direct tours. The direct tours are S1-D1-S1 and S2-D2-S2. The backhaulage route is S1-D1-S2-D2-S1

mainly comprising of 50% added fuel consumption and some additional maintenance costs, which roughly equals 7% of β (Löfroth *et al.* [12]).

We denote the set of feasible backhaul routes R^b. A backhaul route k is defined by a set of direct tours, $R^b(k) = \{r_1, ..., r_p\}$, denoting the p individual direct trips of the route. A *feasible* backhaul route is defined as any backhaul route that reduces the distance travelled without load, compared to making the same haulage tasks by direct tours. Feasibility also means that the total distance of the route is less than a certain maximum limit (e.g. equal to the maximum working hours during one day).

Taking the example given in Figure 2 we will calculate the benefit for the transport buyer of the complex tour, k. We start by calculating the empty distance saved, $e(k)$, in the backhaul route, compared to doing the haulage in two separate direct tours. We have $e(k) = d_{11} + d_{22} - d_{21} - d_{12}$, or more generally, $e(k) = d^l(k) - d^u(k)$, where $d^l(k)$ is the total *loaded* distance of tour k and $d^u(k)$ is the *unloaded* distance. These functions are defined as

$$d^l(k) = \sum_{r \in R^b(k)} d(r), \tag{1}$$

$$d^u(k) = \sum_{r=2}^{p_k} \left(d\left([i_r, j_{r-1}]\right)\right) + d\left([i_1, j_{p_k}]\right). \tag{2}$$

The benefit of the haulage route k for the transport buyer becomes $e(k)\rho$, and so the net cost of a backhaul route k can be expressed as $c^b_k = \sum_{r \in R^b(k)} c^d_r - e(k)\rho$. The haulier will make a net earning of $e(k)(0.93\beta - \rho)$ on the same route. We will in the remainder of the paper focus on the net cost and benefit for the transport buyer which in Sweden usually is the same as a wood supplier having the responsibility for the logistics to the receiving industry. The benefit for the haulier should however not be neglected. The parameter ρ (as well as β) is subject to negotiations between the wood supplier and the haulier. Should the value of ρ become too high in relation to β, the incentive for the haulier to do backhauling would be small, and none should be carried out either. The haulier incentive is vital in Sweden since operative planning and routing of the truck fleet is normally not done centrally by the wood supplier, but is decentralized to the individual haulier, or the association to which the haulier belongs. The wood supplier, however, have the responsibility of defining the haulage tasks (from supply to demand point) and can in that respect influence the potential for finding backhauling opportunities. It is therefore relevant to account for backhauling already in the tactical planning when the wood allocation is settled. If potential backhaul routes can be identified during this planning it is also possible to coordinate the individual operative planning of the hauliers who may have difficulties in finding backhauling opportunities among the haulage tasks they have been assigned to execute.

3 The model

The transportation problem with direct trips can be formulated as a Linear Programming (LP) problem, and can thus be solved efficiently by any commercial LP-package. The problem can be formulated as

[**P1**]

$$\min \sum_{[i,j]\in R^d} c_{ij} y_{ij} \tag{3}$$

$$\textbf{s.t.} \quad \sum_{j:[i,j]\in R^d} y_{ij} \leq S_i, \quad \forall i \in I \tag{4}$$

$$\sum_{i:[i,j]\in R^d} y_{ij} \geq D_j, \quad \forall j \in J \tag{5}$$

$$y_{ij} \geq 0, \quad \forall \quad [i,j] \in R^d. \tag{6}$$

In this model, the variables y_{ij} define the amount transported from supply point i to demand point j and c_{ij} is the related cost per unit of flow. The volume at supply point i is denoted S_i and the demand at demand point j is D_j. The objective is to minimize the total transportation cost subject to restrictions preventing from neither exceeding supply at the supply points, constraint (4), nor falling below the demand at demand points, constraint (5).

In order to be able to include backhauling opportunities in the formulation, we need to modify the notation. The reason is that backhaul routes, as we have defined them above, cannot be expressed using the straight-forward notation of [**P1**]. We define two parameters

$$
\begin{aligned}
a_{ik}^d &= \begin{cases} 1, & \text{if trip } k \text{ picks up at supply point } i \\ 0, & \text{otherwise} \end{cases} \\
b_{jk}^d &= \begin{cases} 1, & \text{if trip } k \text{ delivers to demand point } j \\ 0, & \text{otherwise} \end{cases}
\end{aligned}
$$

If we look at a direct trip k going from supply point i to demand point j we will have only one nonzero coefficient in each of the vectors $\mathbf{a}_k^d$ (vector of dimension m) and $\mathbf{b}_k^d$ (vector of dimension n). These elements are positioned at indices i and j respectively. The model [**P1**] can be expressed (equivalently) in the new notation as

[**P2**]

$$
\begin{aligned}
& \min \sum_{k \in R^d} c_k^d x_k^d && (7) \\
\textbf{s.t.} \quad & \sum_{k \in R^d} a_{ik}^d x_k^d \leq S_i, \quad \forall i \in I && (8) \\
& \sum_{k \in R^d} b_{jk}^d x_k^d \geq D_j, \quad \forall j \in J && (9) \\
& x_k^d \geq 0, \quad \forall k \in R^d. && (10)
\end{aligned}
$$

In this model we have kept the notation R^d to denote all direct trips k. We now include the set of backhaul routes, R^b. The variable defining the flow in backhaul route k is denoted x_k^b. We define

$$
\begin{aligned}
a_{ik}^b &= \begin{cases} 1, & \text{if trip } k \text{ picks up at supply point } i \\ 0, & \text{otherwise} \end{cases} \\
b_{jk}^b &= \begin{cases} 1, & \text{if trip } k \text{ delivers to demand point } j \\ 0, & \text{otherwise} \end{cases}
\end{aligned}
$$

For a backhaul route comprising of two direct tours we have two nonzero elements in $\mathbf{a}_k^b$ and $\mathbf{b}_k^b$, respectively. The vectors can also be defined as

$$
\begin{aligned}
\mathbf{a}_k^b &= \sum_{r \in R^b(k)} \mathbf{a}_r^d && (11) \\
\mathbf{b}_k^b &= \sum_{r \in R^b(k)} \mathbf{b}_r^d && (12)
\end{aligned}
$$

The expanded model with backhaul routes becomes

[**P3**]

$$\min \sum_{r\in R^d} c_r^d x_r^d + \sum_{k\in R^b} c_k^b x_k^b \tag{13}$$

$$\textbf{s.t.} \sum_{r\in R^d} a_{ir}^d x_r^d + \sum_{k\in R^b} a_{ik}^b x_k^b \leq S_i, \quad \forall i \in I \tag{14}$$

$$\sum_{r\in R^d} b_{jr}^d x_r^d + \sum_{k\in R^b} b_{jk}^b x_k^b \geq D_j, \quad \forall j \in J \tag{15}$$

$$x_r^d \geq 0, \quad \forall r \in R^d \tag{16}$$

$$x_k^b \geq 0, \quad \forall k \in R^b. \tag{17}$$

The constraints ensuring supply and demand consistency (14 and 15) now include the variables that define the flow generated in the backhaul routes in addition to those for the direct tours. The above notation could in principle be condensed by not having separate variables for direct and backhaul tours, but we make the distinction for sake of clarity.

4 A numerical example

In order to give the reader an idea of the proposed model, a simple example is given below. The example also shows how optimal decisions in model [**P3**] may differ from the basic model [**P2**]. Figure 3 shows the location of supply and demand points in the example.

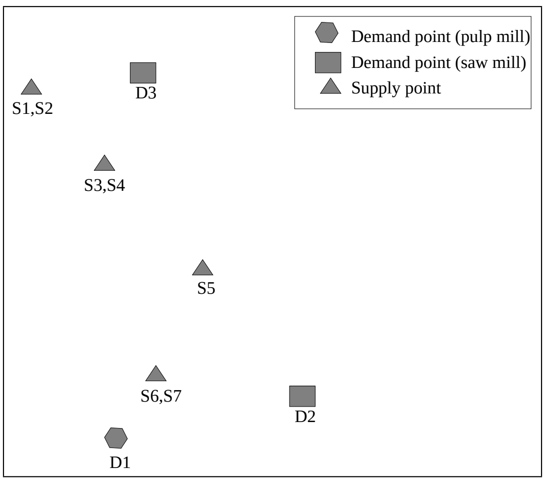

Figure 3: Locations of supply and demand points in the example.

Table 1 contains a distance matrix and Table 2 gives supply and demand data. Two assortments (saw and pulplogs) are used in the example.

The structure of the constraint matrix for the proposed model is illustrated below. In

Supply points	Demand points		
	D1	D2	D3
S1, S2	95	123	32
S3, S4	70	92	30
S5	64	50	64
S6, S7	32	40	95

Table 1: Distance matrix for the example.

Supply (S) /Demand (D) point	Assortment	
	Sawlogs	Pulpwood
S1	500	-
S2	-	500
S3	500	-
S4	-	500
S5	500	-
S6	500	-
S7	-	500
D1	-	1500
D2	500	-
D3	1500	-

Table 2: Supply and demand at supply and demand points for the example.

the example we have 11 direct tours. The number of backhaul routes is large and we just give a few.

$$\begin{aligned}
\min \quad & [c_1 + c_2 + \ldots + c_{11}]^T \mathbf{x}^d + [d_1 + d_2 + \ldots]^T \mathbf{x}^b \\
\textbf{s.t.} \quad & \begin{bmatrix} 1&1&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0 \\ 0&0&0&1&1&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&1&1&0&0&0 \\ 0&0&0&0&0&0&0&0&1&1&0 \\ 0&0&0&0&0&0&0&0&0&0&1 \\ 0&0&1&0&0&1&0&0&0&0&1 \\ 1&0&0&1&0&0&1&0&1&0&0 \\ 0&1&0&0&1&0&0&1&0&1&0 \end{bmatrix} \mathbf{x}^d + \begin{bmatrix} 1&1&1& \\ 1&0&0& \\ 0&1&0& \\ 0&0&1& \\ 0&0&0& \\ 0&0&0&\ldots \\ 0&0&0& \\ 1&1&0& \\ 0&1&0& \\ 1&0&1& \end{bmatrix} \mathbf{x}^b \begin{matrix} \leq \\ \leq \\ \leq \\ \leq \\ \leq \\ \leq \\ \leq \\ \geq \\ \geq \\ \geq \end{matrix} \begin{bmatrix} 500 \\ 500 \\ 500 \\ 500 \\ 500 \\ 500 \\ 500 \\ 1500 \\ 500 \\ 1500 \end{bmatrix} \begin{matrix} \text{(S1)} \\ \text{(S2)} \\ \text{(S3)} \\ \text{(S4)} \\ \text{(S5)} \\ \text{(S6)} \\ \text{(S7)} \\ \text{(D1)} \\ \text{(D2)} \\ \text{(D3)} \end{matrix} \\
& x_k^d \geq 0 \ \ \forall k \in R^d, \ \ x_k^b \geq 0 \ \ \forall k \in R^b.
\end{aligned}$$

Based on these data, the haulage cost was minimized using both [**P2**] and [**P3**]. Figure 4 shows the optimal allocation of *sawlogs* for the two cases. Optimal pulpwood allocation is the same in both cases because there is only one destination for that assortment. From the results shown in Figure 4, it is apparent that, under certain circumstances, optimal decisions may differ between the two formulations, since [**P2**] does not account for backhauling. It is not easy to see the optimal solution even though it is a very small example. For example, in one case the sawlogs are transported a longer distance in order to make it possible to take a backload of pulpwood, which reduces the total cost of all transports.

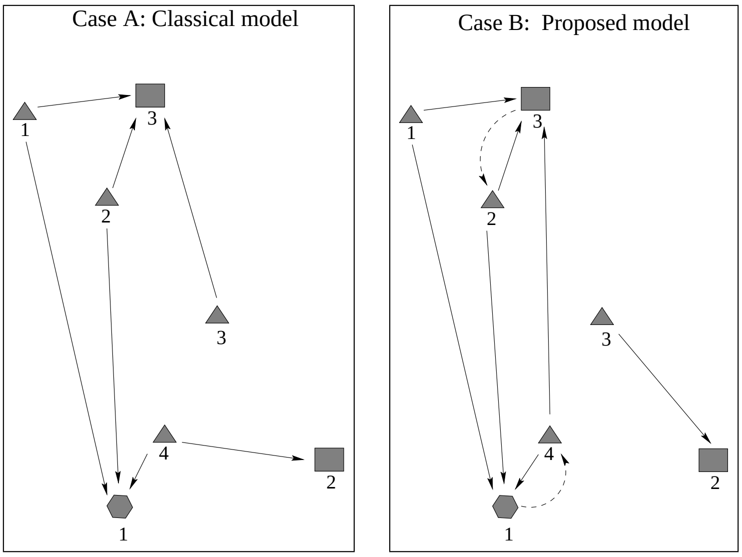

Figure 4: Optimal destination of roundwood in two cases. In the first case (Case A) a classical minimization of haulage work is effected. In this case, sawmill 2 is supplied from origin 4 with 500 m^3. In the second case (Case B), the proposed model is applied in which backhauling is accounted for. In this case, sawmill 2 is supplied from origin 3 instead, because the sawlogs at origin 4 may be carried on a backhaul route with a pulpwood load, which reduces the distance covered by the empty truck (thin solid/dotted lines).

5 Solution approach

The size of the proposed model grows rapidly with the number of supply and demand points included in the problem. At a tactical level, however, planning can be handled on an aggregate level in which one supply point represents a number of harvest areas from which haulage will be carried out. Assortments are often handled in groups with similar characteristics. By choosing an appropriate level of aggregation, a solution to the problem can be found by an enumeration of all possible backhaul routes. For larger, practical problems, complete enumeration is not possible. In these cases, formulation [**P3**] can be solved using a *column generation* procedure. Column generation is a technique where columns to an LP model are generated dynamically.

In the column generation procedure we suggest, see Figure 5, the problem is divided into two levels. At the upper level we have a Master problem consisting of all direct tours and a limited number of backhaul routes. It is initialized with no backhaul routes, in this case the problem is equivalent to [**P2**]. Given the solution we get a dual solution. This information can be used to define a subproblem in which the most negative reduced cost backhaul route is found. In many application only this new column is added to the master problem. It is however also possible to scan a pool of pre-generated backhaul routes. Routes in the pool that have a negative reduced cost can also be added to the Master problem which is resolved. This process is repeated until some convergence criteria is satisfied. One such criteria is that no additional backhaul route with negative reduced cost can be found. A second could be that a specific number of iterations are done.

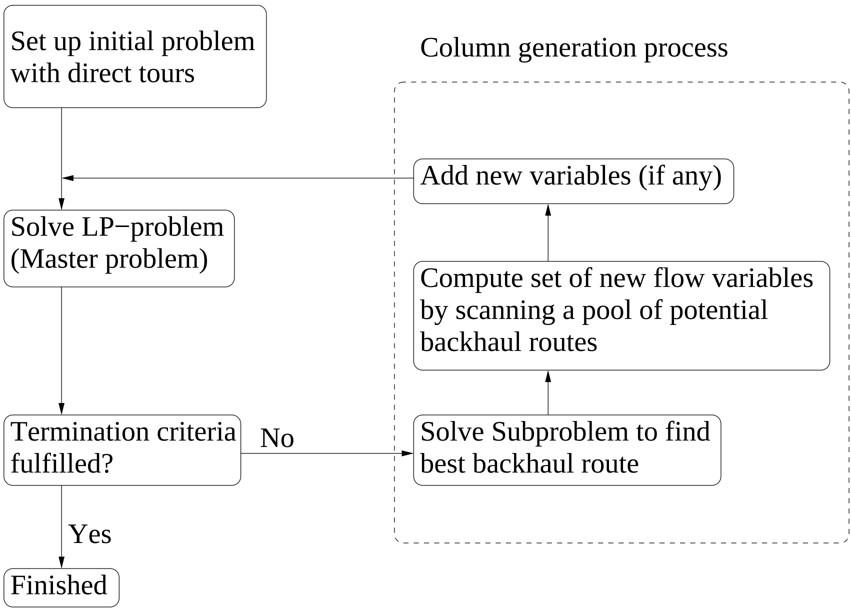

Figure 5: Illustration of the column generation procedure.

In Figure 5 two basic approaches for generating columns are integrated. The first is to formulate a constrained shortest path in order to find the most negative reduced cost backhaul route. The second is to pre-generate a pool of possible or potential routes. This can be used in a pseudo-column generation approach where the pool is searched and the best or a set of best routes are selected to be included into the Master problem. If all potential backhaul routes are included in the pool the two approaches will result in the same optimal solution. In many applications all practical routes can be generated and kept in a pool. Here it is important to note that the pool of routes is not explicit included in the LP solver.

5.1 Subproblem in the column generation method

Every direct tour in the master problem has a reduced cost, $\overline{c}_k^d$, associated with it. This value reflects the potential saving if a direct tour were selected as entering variable in the Simplex method. This value can also be used to establish the reduced cost of backhaul routes not yet generated. Due to the way the cost for direct tour and backhaul routes is calculated (described earlier), the reduced cost for a backhaul route is essentially a linear combination of the reduced costs for the included direct tours with an adjustment for the shortened distance of travel. Hereby it is simple to construct backhaul routes as well as determining the reduced cost.

The reduced cost for a direct tour can be computed by

$$\overline{c}_k^d = c_k^d - (\mathbf{a}_k^d)^T \mathbf{u} - (\mathbf{b}_k^d)^T \mathbf{v} \tag{18}$$

Here $\mathbf{u}$ and $\mathbf{v}$ are dual variables coupled with the supply and demand constraints in model [**P3**] respectively. Reduced costs for potential backhaul routes may be calculated as

$$\overline{c}_k^b = c_k^b - (\mathbf{a}_k^b)^T \mathbf{u} - (\mathbf{b}_k^b)^T \mathbf{v} \tag{19}$$

However, the composition of $(\mathbf{a}_k^b)$ and $(\mathbf{b}_k^b)$ is not known before the exact composition of the tour is known. As backhaul routes essentially are combinations of direct tours we can compute the reduced cost with

$$\begin{aligned} \overline{c}_k^b &= c_k^b - \sum_{r \in R^b(k)} (\mathbf{a}_r^d)^T \mathbf{u} - \sum_{r \in R^b(k)} (\mathbf{b}_r^d)^T \mathbf{v} && (20) \\ &= \sum_{r \in R^b(k)} \overline{c}_r^d - \rho_k. && (21) \end{aligned}$$

To get a feasible route we must satisfy a maximum length (in time) of a route. In order to find the composition of a feasible backhaul route we can formulate a constrained shortest path problem. The general network flow problem (including shortest path problems) with one capacity constraint on time can be formulated as

[**Sub**]

$$\begin{array}{lrcll} \min \ z = & \displaystyle\sum_{(i,j) \in B} c_{ij} z_{ij} & & & \\ \textbf{s.t.} & \displaystyle\sum_{i:(i,k) \in B} z_{ik} - \sum_{j:(k,j) \in B} z_{kj} & = & b_k, & k \in N \\ & \displaystyle\sum_{(i,j) \in B} t_{ij} z_{ij} & \leq & T_{max} & \\ & z_{ij} & \geq & 0 & (i,j) \in B \end{array}$$

Here, z_{ij} is the flow on arc (i,j), B is the set of arcs and N the set of nodes. The structure of the constrained shortest path problem for our application with backhauling is illustrated in Figure 6. The nodes *Start* and *End* are start and end nodes of the shortest path we search. The remaining nodes are representing the transportation problem with supply and demand points. When we have a shortest path we have that the node balance b_k is 0 for all nodes except for nodes *Start* and *End* where it is -1 (source) and +1 (sink) respectively. The coefficient t_{ij} is the time taken to use arc (i,j) and T_{max} is the time limit for any backhaul route.

Based on the cost structure described in Section 2 we have the possibility to distribute the cost among all arcs in any tour. Arcs from *Start* and to *End* have no costs associated. Arc costs including the dual information between supply i and demand j can be defined as

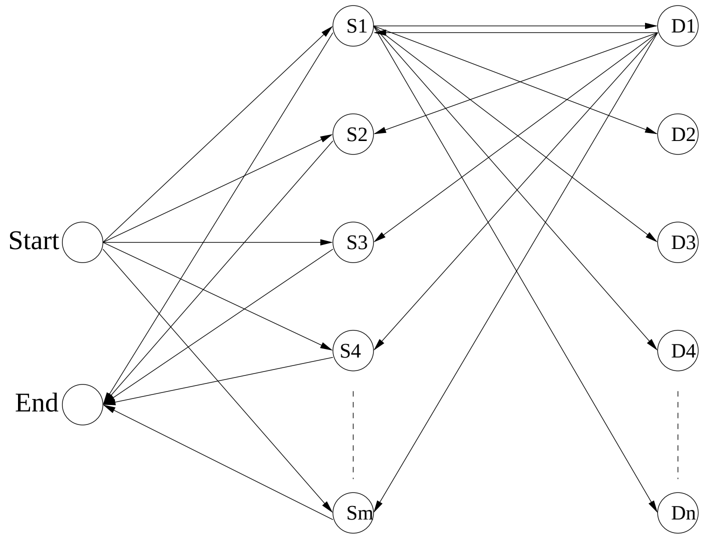

Figure 6: An illustration of a graph where we can represent problem [**Sub**] as a constrained shortest path problem from a start to an end node. Not all arcs are included.

$$c_{ij} = \alpha + (\beta - \rho)d_{ij} + u_i, \qquad \text{(forward flow, supply - demand)} \tag{22}$$

$$c_{ji} = \rho d_{ji} - v_j \qquad \text{(backward flow, demand - supply)} \tag{23}$$

Problem [**Sub**] can be solved using methods described in e.g Desrosiers et al. [3]. If the shortest path has a negative reduced cost, it exist a backhaul route to include into the Master problem. Otherwise, we have solved the Master problem to optimality and can stop the column generation process. An example of implementation of a column generation (which is also used in some of the systems to be described) for [**Sub**] is given in Isaksson [11]. In this paper a comparison is given on the computational time and efficiency comparing the proposed solution of a sub-problem with using a pre-generated limited pool of backhaul routes. It is noted that the network can be reduced by using nodes representing the geographical locations instead of supply and demand nodes. The number of such geographical nodes is fewer as there are generally several supply nodes in each location due to several assortments. The calculation needs to be updated such that the minimum cost arc (representing many potential combinations of supply and demand points) between any pair of geographical nodes is used.

Instead of solving [**Sub**] we can generate, as mentioned earlier, a pool of potential backhaul routes. When a specified number of routes with negative reduced cost have been found the generation phase is stopped. This approach works well, as found in Isaksson [11], when the routes only consists of two direct tours. This is also a practical restriction imposed by most companies. One reason is the problem of finding a fair cost distribution between tours if different hauliers are responsible for each of the tours. Another practical limit often imposed is that the backhaul should have a certain reduction in the unloaded proportion. For example, if the direct tours have an unloaded length L then the backhaul route must have an unloaded length of, say, at most 0.90L (i.e. length no more than 90%).

6 Case studies

The backhauling model has been applied in a number of case studies for companies in different geographical regions (see e.g. Holmgren [10] and Forsberg [6, 7]). Here we present some cases in order to demonstrate the usage of backhauling and performance of the solution methods. We have four case studies done at three forest companies; these are AssiDomän AB, Sydved AB and Mellanskog. The geographic locations of the case studies are given in Figure 7. The purpose of the studies were to establish the potential savings of the transportation costs using backhauling. Interesting is also to study the size of the model for real-world data and the required computing times. In the presentation of the results, backhauling tours with more than two loaded trips have not been considered in the analysis. Only the heuristic column generation approach with a pool or routes has been used. Accounting for tours with three or more loaded trips increases the size of the problem considerably, due to its combinatorial nature. Tests showed, however, that only a marginal further reduction of the cost would be achieved with routes including many direct tours.

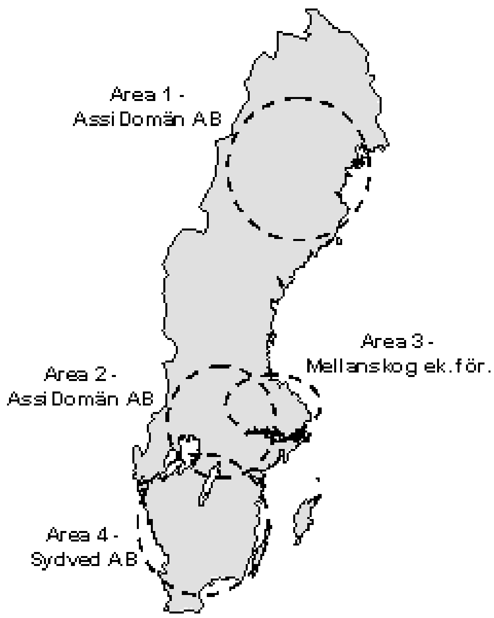

Figure 7: Geographic locations of the four case studies.

In all studies, historical data were gathered on haulage operations that had been carried out during one week. The supply and demand were calculated from these data. Detailed information about volumes carried in backhauling tours were not available for any of the areas. However, according to transport managers, only marginal quantities were subject to backhauling during this period. The cost function parameters α, β and ρ was set to 1.8, 0.045 and 0.013 respectively in all of the case studies which relates to actual values used at the companies. Characteristics of the test areas are given in Table 3 and the optimization results are summarized in Table 4 and 5.

Area	Number of:			Volume per assortment group			Historic
	Supplies	Demands	Assort.	Sawlogs	Pulpwood	Total	cost
1	96	29	18	22,192	8,040	30,232	171.1
2	66	27	17	30,495	18,173	48,668	210.8
3	65	17	16	9,704	10,075	19,799	72.5
4	128	40	8	15,845	83,144	98,989	613.0

Table 3: Characteristics of the test areas (volumes in m^3 and costs in US$1,000s.)

Area	Obj. value	Reduction	No. direct tours
1	167.0	2.4%	3,125
2	206.2	2.2%	1,911
3	72.2	0.4%	472
4	595.2	2.9%	1,775

Table 4: Results based on formulation [**P2**] (costs in US$1,000s).

Area	Obj. value	Reduction	No. backhaul routes	No. iterations
1	162.1	5.3%	2,133	22
2	196.5	6.8%	3,233	33
3	68.8	5.1%	1,001	10
4	574.1	6.3%	1,651	17

Table 5: Results based on formulation [**P3**] (costs in US$1,000s).

The results show that model [**P2**] give better solutions compared to the actual deliveries during the week. Furthermore, optimization with the proposed model [**P3**] give lower objective values compared to those obtained upon optimization with [**P2**]. The effects are ranging from 5.1-6.8%. Actual haulage in Area 3 was nearly optimal compared to what could be achieved with [**P2**] (see Table 4). The objective value was reduced with only 0.4% compared to the historic cost. However, if backhauling is considered results in Table 5 shows that a five percent reduction would be possible.

From a practical point of view, the effects of backhauling in terms of reduction in unloaded driving and fuel consumption are of great importance. In Table 6 the savings that are possible within the studied areas are given. Almost one third of the unloaded driving in Area 2 can be saved. This will in the long run e.g. reduce costs for maintenance of the road network. Emissions of pollutants (CO_2, CO, HC and NO_x) will also be reduced since they are proportional to the consumption of fuel. The fuel savings given in Table 6 thus shows that backhauling is also good for the environment.

Area	Savings in terms of unloaded distance, km	fuel consumption, liter
1	10,510 (16%)	3,153 (4.8%)
2	18,603 (28%)	5,581 (8.4%)
3	6,664 (22%)	2,000 (6.7%)
4	40,411 (18%)	12,124 (5.3%)

Table 6: Savings due to backhauling with respect to unloaded distance and fuel consumption.

# generated routes	# iter	Tot # backhaul routes
10	194	1,939
50	58	2,933
100	33	3,233
200	19	3,818
500	9	4,525
1000	5	5,236
2000	3	6,027

Table 7: Effects on the solution process from changes in the number of columns generated in each iteration of the solution process.

All the cases were solved in less than a second using CPLEX Callable Library on a Pentium-1.6GHz computer under Windows-XP. The column generation needs between 10 to 33 iterations to find the backhaul routes needed in an optimal solution. In each iteration, 100 potential routes were generated. The number of backhaul routes included in the problem when it reaches optimum is only a small fraction of the total number of possible obtained upon a complete enumeration. Such an enumeration for Area 2 produced some 150,000 tours, which should be compared to the 3,233 generated during the optimization process.

During the solution of the optimization problems of the above case studies the column generation was set to produce 100 potential backhaul routes in each iteration. By generating several routes per iteration the solution process is faster. However, when generating several routes the master problem grows larger and using more of the computers internal memory. In Table 7, the effects on problem size by changing the number of tours to be generated in each iteration is exemplified for case study 2 above. The generation phase in the proposed algorithm is very fast.

7 Decision support systems using backhauling

Backhauling is an importrant part in some decision support system. In this section we describe these systems and comment on some of the results.

7.1 Wood sorting at Södra Skog

In Carlgren *et al.* [1] backhauling is combined with optimization of wood sorting policies at Södra Skog. This system is used by Södra Skog to analyze which assortments to purchase in different geographical areas. The background for this model is the continuously increasing demand from pulp and paper producers to be supplied with wood having specific properties for a certain product. One way of dealing with this problem is to sort the wood into a larger number of assortments each having more specific characteristics, which can be directed to different industries based on desired properties. This will lead to an increased average transportation distance since the wood to a lesser degree is delivered to the nearest receiver. It will however also lead to improved backhauling opportunities since wood is increasingly going in different directions. The problem dealt with in this case is to decide how the wood should be sorted during harvesting in different geographic areas while accounting for the backhauling possibilities.

The problem is modeled as a mixed integer model in which the sorting decisions are binary, i.e. only one sorting option can be used in each area. Backhauling tours are iteratively added in a column generation procedure. The model proposed in Carlgren *et al.* [1] is applied in some case studies, and is proven to be solvable quickly for practical problem dimensions. Based on results from the case studies, backhauling is shown to reduce the increase in transportation costs caused by added sorting complexity. Including backhauling in the optimization also affects the optimal sorting decisions as is illustrated by Figure 8.

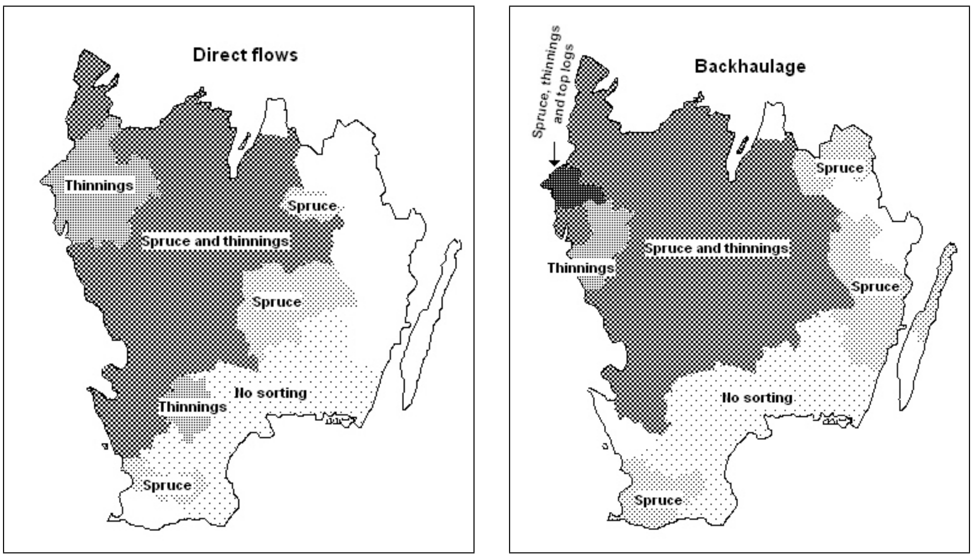

Figure 8: Sorting decisions when backhauling is not included (left) and when it is (right).

7.2 Web based system Åkarweb at Holmen Skog

The backhauling model has also been integrated into a haulage web (*Åkarweb*) developed by one of the major industrial forest enterprises in Sweden, Holmen Skog (see Eriksson and Rönnqvist [4] and Frisk [9]). Holmen Skog is using some 180 trucks for their wood haulage in the northern part of Sweden. The operative planning of these trucks is decentralized to the individual haulier. Holmen Skog defines the haulage task, i.e. to which destination each pile of logs should be hauled. A haulier usually gets all the tasks within a specific geographical area. The main advantage with this is that hauliers are well aware of the conditions within their geography. A disadvantage is that hauliers have difficulties in finding backhauling opportunities within their own area.

The main purpose with the haulage web is to support the decentralized wood haulage management. This is achieved partly by providing updated information on the current location of logs piled at the road side, and to which industry it has been allocated. In addition, the system also provides information about potential backhaulage combinations. The haulier can in the system identify the haulier responsible for the backhaulage task and coordinate the planning with him. Once a day (in the morning) the system is updated with backhauling options based on information about the haulage tasks being updated during the night.

The backhauling model is in this case used in an *operative* planning context, even though it initially has been designed for tactical planning. Frisk [9] report positive reactions by hauliers on the system. The main results related to reduced time for planning since all relevant information is easily accesible through the system. There is no need to call e.g. harvesting entrepreneurs to update available volumes at different supply points. The study identified a potential to increase backhauling by almost 400%. The overall cost reduction by introducing the system is found to be 5-10%.

7.3 The decision support system FlowOpt

FlowOpt is a decision support system for transportation planning in Swedish forestry, developed by the Forestry Research Institute of Sweden in collaboration with Linköping University (see Forsberg *et al.* [8]) and five major Swedish forest companies. The system deals with the general wood transportation problem as illustrated in Figure 9. Haulage is either carried by trucks directly from the harvest area to the receiving industry, or by a combination of trucks and train, where the trucks are necessary for the transportation to reloading terminals. A number of strategic and tactical questions are linked to this problem such as design of the train system (location of terminals, capacity etc.), definition of catchment areas and identification of backhaulage tours.

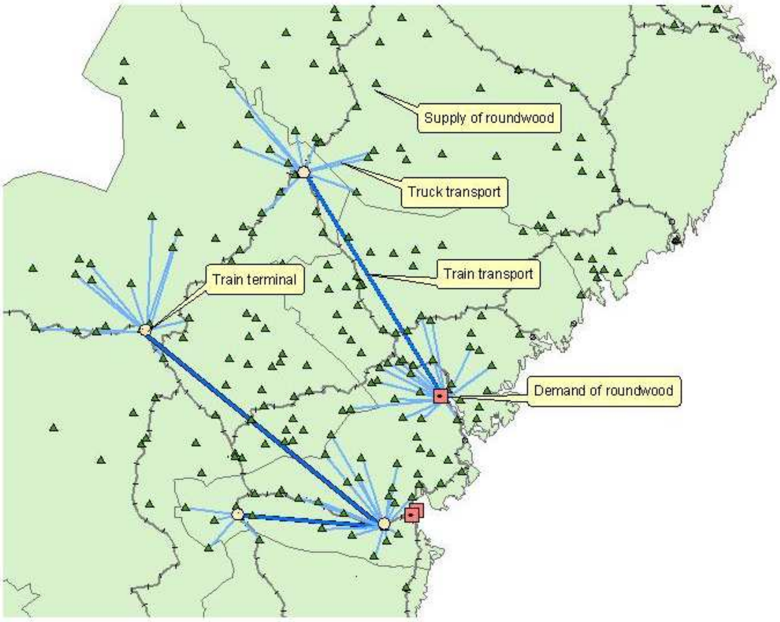

Figure 9: Illustration of the general transportation problem handled by FlowOpt. The transportation is carried out by a combination of trucks and trains.

The problem is formulated as a Linear Programming model, which includes variables for direct haulage, backhaulage and train transportation. Constraints are defined for supply and demand consistency, terminal and train link capacity, and terminal balance. The model is implemented in AMPL and solved using the commercial solver CPLEX. The optimization application is linked to the main application of FlowOpt, which contains functions for calculation of haulage distances, generation and editing of data, and mapping. The main application creates input files for the optimization application and imports the result files generated by the optimization. Results are compiled into Excel reports and GIS-maps. Figure 10 gives an overview of the different components of the system. The system is linked to the Swedish National Road database (NVDB) for the distance calculations.

Two case studies using of FlowOpt are reported in Forsberg *et al.* [8]. The first case deals with strategic design of a train system for the forestry enterprise *Sveaskog*. The problem involves 124 supply areas, 15 assortments and 115 demand points. The train system consisted of six potential locations of train terminals and six potential train routes. The optimization problem generated by FlowOpt consists of more than 20,000 variables and 1,500 constraints. The number of potential backhauling routes exceeds half a million. FlowOpt was used to optimize the wood flow with and without the use of the train system. Comparisons of the results showed that the train system was profitable, even though backhauling offered a greater cost reduction in the case without the train system.

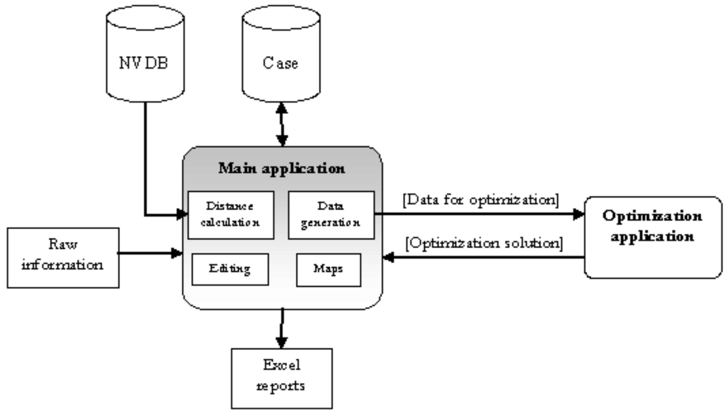

Figure 10: Overview of the FlowOpt-system.

The other implementation deals with bartering of wood between the forestry enterprises Holmen Skog and Södra Skog. The pupose of the bartering is to reduce transportation costs by hauling the wood to the nearest pulp industry irrespective of which of the companies being formally responsible for supplying the industry. This is relevant since both companies are competing for the wood in the same geographic area. The purpose of the FlowOpt-analysis is to find the optimal volume to barter each month and in which areas the exchange should take place. The case involves more than 2,000 supply areas, sixteen demand points and six assortments. The optimiziation problem includes more than 11,000 variables and almost 1,300 constraints. The number of potential backhauling routes in this case exceeds 100,000. Results from FlowOpt showed that the bartered volume could be doubled by which a cost reduction of about 5% was estimated. In both implementations FlowOpt managed to perform the optimization and generate result reports quickly. In [8] the size of some even larger cases than the above involve several hundred millions potential backhauling routes.

8 Discussion

Two major questions have to be addressed before any practical use of the proposed model in tactical planning: Who should be responsible for the system and run it? How should the model be supplied with data? How should savings be allocated to participants? The first question becomes especially difficult if coordination involves several companies. In some regions all hauliers within the region may belong to an association of hauliers, in which case the association may coordinate their transportation for different forest companies. However, in other cases there are several associations in the same geographic region and also some hauliers not belonging to any association at all. In these cases the solution might be to engage a company whose sole responsibility would be to take care of the coordination.

In order to utilize backhauling, trips have to be coordinated between different transport managers and different forest companies. The purpose of the model proposed above is to facilitate coordination on the tactical level. Results from the model indicate the supply and demand points between which backhauling is optimal. Based on this information, transport managers have the option to contact other managers that might be involved and thus improve their operative planning. This is the type of support that has been integrated into the *Åkarweb* system. The model could also be an important subsystem in a future system for roundwood flow management, providing a link between the long-term housekeeping objectives and the short term demand and haulage cost objectives that predominate in operative planning (compare *FlowOpt*).

This solution may also facilitate the problem with data supply. Information concerning supply of roundwood may in some situations be sensitive. It should not be available for competitors, i.e. those with which transportation should be coordinated. If information is gathered by the neutral transportation coordinator, which is not involved in the competition for roundwood, this problem might be overcome.

If a number of companies are coordinated there will be some savings compared to the case where they operate by themselves. This savings should be distributed among the participating companies in a fair way. There are however a number of aspects to consider. No companies or group of companies should have an incentive to withdraw and start up cooperation themselves. The distribution should not lead to problems in subsequent planning, e.g., if one company receives a larger proportion than motivated. The size of the companies do also have an affect in how the coordination can be initialized. This is interesting for future research.

9 Concluding remarks

The tactical problem has historically been solved manually without any possibility of coordinating many supply and demand points with respect to backhauling. We have described an LP based flow model which supports the transportation managers with information about good backhauling alternatives. In addition, it suggest how harvest areas can be combined into suitable catchment areas for the industry. The solution procedure is based on column generation which make efficient use of the fact that the potential routes are essentially linear combinations of direct flows in a traditional transportation model. We have also suggested an approach to generate a backhaul route where the number of loaded trips becomes large. Numerical results from case studies and systems indicate a large potential for savings in both direct costs as well as in a decrease in pollution.

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