Extraction of Logs in Forestry Using Operations Research and Geographical Information Systems

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Abstract

An important and so far much neglected operative problem in the Swedish forestry is to extract roundwood from actual harvest areas to load points at forest roads. Once at the load point, logging trucks can collect it for further secondary transportation to saw- and pulp-mills. We report on a system being developed which collects geographic information by a global positioning system (GPS) about logpiles and actual routing network used by the forwarder. This is stored together with related information in a geographical information system (GIS). Using operations research (OR) techniques we can find high quality routes. This provides the driver with an operative tool in finding routes. We give numerical results from a case study done for a major Swedish forest company.

1. Introduction

Forestry is of major importance to the Swedish economy. The total value of exported forest products was SKR 95 billion (approximately US 12 billion) in 1995 which accounts for 17% of the total value of Swedish exports. Being heavily dependent on the export market, the Swedish forest industry has to ensure that its prices are competitive. This means that it has had to increase or maintain the efficiency of all its operations from stump to dockside.

The need to increase productivity has been a major incentive for rationalization of harvesting operations. In 1950 the productivity was about 1.2 m³/man-day which had increased eleven times to about 14 m³/man-day in 1992. Heavy rationalization has been very important for Swedish forest industries to cope with international competition. The drastic increase in mechanization between 1974 and 1996 is given in Figure 1. However, considering that mechanization is almost complete, the potential for dramatically increased cost efficiency in harvest operations seems to be small.

A general opinion in Swedish forestry today, is that the potential rather lies in improved integration between different parts of the wood-flow chain. Furthermore, customer orientation is at the center of attention. The idea is that the correct quality and amount of raw materials should be delivered to the customer at the right time. By this, the customer has the opportunity to improve on the utilization of the raw material as well as in production planning. Hereby, both a decrease in processing costs as well as an increase in product value may be achieved. Customer orientation will dramatically increase the demands put on the logistics system in Swedish forestry. The number of assortments will increase as well as the need and request for timed deliveries. Storage must be reduced since maintaining the inherent quality of the raw material until it is delivered, is one of the basic ideas of customer orientation. Several operative problems are described in Carlsson and Rönnqvist [5].

![Figure 1: Mechanization levels in Swedish forestry (Nordlund 1996).](image)

To cope with these demands, transportation will have to be carried out in an optimal or near optimal way. For example, while having to travel further away from customers to collect a sufficient amount of specific raw materials, efficient routing and scheduling of
trucks is a mean of moderating the increase in transportation. As the planning becomes increasingly complicated there is a need to assist the planner with operative tools. OR techniques can be used to suggest e.g. routes and overall flows. However, to use such techniques there is a need to have access to information about e.g. actual roads, supplies and orders. It should also be easy to collect and update the information. GIS provide that link to the OR tools.

An important operative problem is to extract roundwood from actual felling points to forest roads. Once at the pickup point, logging trucks collect it for further secondary transportation to saw- and pulp-mills. The actual extraction problem is to move logpiles in as short time as possible from the felling piles to the pickup point. Harvesting of full trees are mechanized and there are two types of vehicles operating in the forest. The vehicle which actually fell and buck trees is the harvester. The harvester puts the bucked logs in small piles based on assortment as it moves around. These piles are then collected by a forwarder and moved to larger piles adjacent to forestry roads. In principle all sawlogs are extracted by a forwarder for the first distance. The overall cost for this operation is estimated to be $US 200-250 million. A small increase in efficiency may obviously have a large impact on operational costs. The trend is also that the number of assortments i.e. the number of different piles is increasing, making operations both increasingly difficult and more costly.

In this paper, we describe a prototype for a system that integrates GIS and OR techniques. We use a GPS system to collect data for the GIS. The outline of the remainder of the paper is as follows. We start by describing the extraction operations in Section 2. We then describe the mathematical model used to find routes. Information needed for the model and how some are constructed is described in Section 4. There are several methods available to solve the model; these are described in Section 5. Numerical results based on a case study from a Swedish forest company are presented in Section 6. We then discuss an extension and make some concluding remarks.

2. Extraction of logs

2.1. The harvester and forwarder

A typical Swedish harvester is given in Figure 2. Harvesters are equipped with on-board computers for bucking decisions. The bucking depends on price lists which may differ from one harvester to another. The price lists are designed in order to give an output, in terms of species and the desired proportions of log lengths in different diameter and quality classes, that corresponds to the demands of the sawmills. Even though bucking is very refined, the logs are delivered in only a few different assortments based on species and dimension.

Figure 2: A typical one grip harvester.

A forwarder works in pair with a harvester and follow very much in the same tracks. This is, in particular, true for thinning operations as the number of possible road selections are limited. The forwarder is normally two to five days behind in operation, and it is, in general, the slower of the two vehicles. A typical forwarder is given in Figure 3.

Figure 3: A typical forwarder.
Forward drivers have different skill levels and experience. Each driver operates according to what he/she believes is the best strategy. This give rise to a problem as this will not be efficient taking several shifts, with different drivers, into account. For example, suppose one driver starts by extracting all assortments from the back of the harvest area while another also starts at the back but concentrates on only one assortment. As piles are collected, the quality of the routes will tend to decrease as the two strategies will give less opportunities, especially towards the end of the operations. Moreover, it is difficult for each driver to be updated with the current situation as different strategies would be in use. Figure 4 illustrates a typical harvest area.

![Figure 4: An illustration of a harvest area.](image)

The forwarder drives along terrain roads of various quality at different speeds depending on terrain and weather conditions. The situation is also very different when we compare e.g. summer and winter conditions. Each trip with a forwarder starts with an empty-driving to the first pile of pick-up. The forwarder then continues to load logpiles until it is fully loaded when it returns to the appropriate pile (or piles) at the pickup point where it unload. A complicating factor is that the forwarder can load several assortments in different loading patterns. The strategy used will result in limitations in the unloading process. This is because it must be unloaded in a particular sequence or time consuming sorting must be done. A skilled driver may be able to sort logs more efficient and hence combine several assortment whereas a less skilled driver avoids sorting operations. Some typical data for the harvesting and forwarding operations is given in Table 1.

2.2. Forwarding operations

There are several possibilities to load a forwarder. Figure 5 give a number of loading patterns. The lower pattern for two assortments can, for example, be loaded in the following sequence: load 2 ton A, load 3 ton A, load 4 ton B, load 2 ton B, unload 6 ton B, and unload 5 ton A. The upper pattern for two assortments gives more flexibility as the assortments can be loaded in parallel. However, it must be loaded in about the same pace. Otherwise it would be a risk that the forwarder will tip over.

![Figure 5: Different loading patterns.](image)

The time to perform one route depends on a number of factors. The most important ones are listed below.

- Total distance travelled, both loaded and unloaded distances.
- The speed of the forwarder at various road types.
- Number of stops. Sometimes it is possible to load more than one pile without moving the forwarder. This is decided by the reach distance of the grip arm and the distances between piles.
- Number of cycles the grip arm is used.
- The loading pattern used. This pattern of course means a lot when it comes to decide which piles to visit and in which order.
- Unloading and sorting. This depends on the loading pattern and the skill level of the driver.

Table 1: Data illustrating a typical large-scale operation.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Average Cut Area Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinning</td>
<td>0.11 52 11 358</td>
</tr>
<tr>
<td>Final felling</td>
<td>0.36 180 12 414</td>
</tr>
</tbody>
</table>


3. Mathematical model

To formulate the mathematical model we introduce the notations and variables given below. This include information relating to each route.

\[ m = \text{number of piles}, \]
\[ b_i = \text{amount of logs in pile } i \text{ (expressed in } m^2), \]
\[ x_j = \begin{cases} 1 & \text{if the forwarder drives route } j, \\ 0 & \text{otherwise}, \end{cases} \]
\[ n_{tot} = \text{total number of possible routes}, \]
\[ c_j = \text{time to drive route } j, \]
\[ a_{ij} = \text{amount of pile } i \text{ picked up by route } j. \]

The mathematical model can now be stated as

\[ \begin{align*}
\min & \quad \sum_{j=1}^{n_{tot}} c_j x_j \\
\text{s.t.} & \quad \sum_{j=1}^{n_{tot}} a_{ij} x_j \geq b_i, \quad i = 1, \ldots, m \\
& \quad x_j \in \{0, 1\}, \quad j = 1, \ldots, n_{tot}. 
\end{align*} \]

We have \( m \) constraints, one for each pile, which states that the logs at all piles must be picked up (by one or several routes). The use of \( \geq \) constraints is to make it easier to find a set of routes giving a feasible solution. In the case when a constraint is "satisfied" we simply decrease any route with the corresponding amount. Any set of routes satisfying the constraints in \([P]\) gives an upper bound of the overall time. With this formulation of the problem, we allow routes to pick up fractions of piles. The rest is left for another route or have been picked up by an earlier one.

In most optimization problems the objective function and all constraints are given explicit from start. In our case things are a little bit different. It is not possible to, a priori, generate all possible routes, since there exists a huge number of them. To give an indication, suppose that we in average can pick up five piles per route and there are 500 piles. This would give a total number of \( 3.06 \times 10^{13} \) routes which is far too many to have in a model. Furthermore, most of these routes are of low quality and would never be used in real life. Therefore, the problem considered in this project falls into two separate problems. The first one is to generate routes dynamically and the second is to solve the overall model. To generate routes we need information about the locations of each pile and its assortment. To compute route times we also need information about distances and time to perform various operations. These aspects are discussed in Section 4.

In real life, properties of piles may differ. For example, some piles are easy to load while others are not. There could be many reasons for that, for example crossed logs in a pile, difficulties to reach the pile etc. In our model we assume that piles have averaged properties. We do not model acceleration and retardation for the forwarder, instead we add a constant time for every stop.

3.1 A small example

To illustrate the model we give a simple example with five piles. Piles one to three consist of saw-logs whereas piles four and five consist of pulp-logs. Data associated with the example is given in Tables 2 and 3.

Table 2: Information regarding assortments and amounts for the piles in the small example.

<table>
<thead>
<tr>
<th>Pile</th>
<th>Assortment</th>
<th>Amount (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>saw-log</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>saw-log</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>saw-log</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>pulp-log</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>pulp-log</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 3: Distance table (minutes) for the example. Node 0 indicate the load point.

<table>
<thead>
<tr>
<th>From-To</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>12</td>
<td>14</td>
<td>9</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

We only generate routes which pick up entire piles. We have also assumed that a pickup always take one minute and unloading (all logs) takes two minutes. Only ten routes which are a fraction of all possible routes is generated. The model is then as follows.

\[ \min \begin{bmatrix} 33 & 26 & 29 & 25 & 27 & 29 & 28 & 30 & 24 & 26 \end{bmatrix} \times \begin{bmatrix} 1.2 \\ 2.2 \\ 0.6 \\ 0 \\ 1.8 \\ 0 \\ 1.4 \\ 0 \\ 1.4 \\ 0 \end{bmatrix} = 1.2 \times \begin{bmatrix} 1.2 \\ 2.2 \\ 1.6 \\ 1.8 \\ 1.4 \end{bmatrix} \]

\[ \begin{align*}
\text{s.t.} & \quad 0.6 \geq 0.6 \\
& \quad 0 \geq 0.6 \\
& \quad 0 \geq 0.6 \\
& \quad 0 \geq 0.6 \\
& \quad x_j \in \{0, 1\}, \quad j = 1, \ldots, 10. 
\end{align*} \]
4. Geographical information

In order to generate routes we need information about the location of piles, which assortment, and a distance table. To find the distances we also need to establish the actual network used by the forwarder. All this information is collected into a GIS system. We have used the MapInfo system to store all information and to view and study the selected routes.

4.1. Assortment piles

To have information about logpiles is not only of interest for the route generation. Suppose there is an urgent demand of a particular assortment at a sawmill. It is then possible for the driver to directly report the actual level of that assortment. This in turn can then be used by the transport manager to direct logging trucks to harvest areas where the assortment is available and/or instruct the drivers to concentrate on extraction of that specific assortment.

We have used a GPS to record the position of each pile and related information about assortment and amount. This information is then inserted into the MapInfo system. In our case we measure amount in terms of an area in $m^2$. The reason for this is that the capacity of the forwarder is limited by the cross-sectional area of the loading wagon. It also has a weight limit but this can easily be expressed in terms of an area. Figure 6 give an example of a geographic view of piles measured at the harvest area used as a case study.

It is possible in MapInfo to select a certain item and request to view related information. In Figure 7, we illustrate information about a specific pile. Here, we give ID number and coordinates of the pile in the first three fields. In the next two fields, we get assortment of the pile and the number of logs. Finally, we have ID numbers of adjacent road points. The MapInfo system can also be regarded as a database. Objects can easily be found using SQL-queries, i.e. questions to make selections. In this way subsets can be derived from original sets and described separately. In Figure 7, only piles of assortment 3 are shown.

![Figure 7](image)

Figure 7: Information stored about a specific pile.

4.2. Routing network

Having access to the assortment piles is not enough as we cannot use Euclidean distances to compute the distance table. Instead we need to establish an actual road network which the forwarder uses. This is an important aspect as there is a need to make as little damage as possible to the ground due to environmental and replanting considerations. Normally, the driver builds a so-called primary or base road to which traffic is concentrated. This primary road crosses the harvest area and it is chosen by the driver’s experience. If it is a large harvest area or there are some special geographic considerations like large streams or steep hills, the driver might choose several primary roads. In addition to the main roads there are secondary roads of smaller size and quality. Moreover, when it comes to the secondary roads, the forwarder tends to follow the tracks of the harvester as all piles will be easily accessible from this track. The size of the road will determine the possible speed of the forwarder when driving, an example is given in Table 4.

![Figure 6](image)

Figure 6: A geographic view of piles measured at a harvest area used as a case study.
Table 4: Different speed on different road types (expressed in meters per minute).

<table>
<thead>
<tr>
<th>Type</th>
<th>Speed loaded</th>
<th>Speed empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary (base)</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Secondary main</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Secondary base</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>Secondary wet</td>
<td>30</td>
<td>50</td>
</tr>
</tbody>
</table>

To find these roads we have used a GPS to measure coordinates along the various tracks. We denote those coordinates road points. An example of collected road points is given in Figure 8. This figure also gives the actual road network when the roads have been identified.

The information about the road points are then used to establish the actual road network. We have used Floyd’s algorithm, see e.g. Bofley [1], to compute the distance matrix between all pairs of road points. Given this distance matrix we can compute any distance. As the number of piles may be very large we have chosen not to build a large distance matrix between any pair of piles. Instead we have computed the distance to the closest road point from each pile. This information together with distance matrix for the road points give the required distances.

4.3. Loading and unloading operations

To compute overall route time we need some additional data. For the travel time we need distances, speeds and number of stops. For the loading time, the number of grip arm cycles and average cycle time is used. The number of cycles depends on the size of the piles and the capacity of the loading arm. The cycle time depends on how many piles can be loaded without moving the forwarder. To load the first pile some initial action has to be performed. Therefore, the cycle time for the first pile (but at the same stop as the loading arm can reach other piles) is longer than for the following piles. When it comes to unloading, the loading pattern also matters. Unload time increases when the number of different assortment loaded increases. The reason is that the driver has to be more careful when unloading, making sure the right assortment gets to the right pile. The capacity of the loading arm in each cycle is in average 0.26 m$^3$ and the overall loading capacity of the loader is 4.5 m$^3$. The average cycle time for the loading time is 25 seconds for the first cycle. For the second, third etc. we have an average time of 16 seconds. Table 5 gives the corresponding unloading times.

Table 5: Average cycle times for the unloading operations depending on the number of assortments.

<table>
<thead>
<tr>
<th>No. of assortment loaded</th>
<th>Averaged cycle time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
</tr>
</tbody>
</table>

5. Solution methods

There are several techniques to solve large scale routing problems. Because of the complexity of the problem many methods are based on the use of heuristics. These heuristics are often based on a specific application and are developed especially for this. We have used two different approaches to solve problem [P]. The first one is purely based on heuristics and the second is a combination of column generation and heuristics. Column generation is a technique which is often used to solve large scale and difficult routing problems.

5.1. Heuristics

We have developed a general heuristic which takes as input some strategical rules. These rules are general and can be used in combination of each other. Some rules which we use and which we can combine is given below. These are closely related to actual drivers
strategies. It is therefore possible to extract a harvest area in a similar way to what would be done by the drivers.

- Build routes with a single assortment
- Build routes with one or two assortments.
- Start from the far end of the harvest area.
- Find piles near the first selected pile. Create a subset of piles that are candidates for being in the route and at the same time do not exceed the loader capacity. Then investigate a number of permutations of those piles, in order to find a good route.

A simple example of a tactical aim is given below. In this example there are three different assortments.

1. Create routes that drives to piles of assortment 1 until 50% of that assortment is extracted.
2. Create routes that drives to piles of assortments 2 and 3 until at least 40% of both assortments are extracted.
3. Create routes that drives to piles of assortments 1 and 3 until all of these assortments are extracted.
4. Create routes containing assortment 2 until all is extracted.

To start at the far end of the area is normal. The reason is that when most piles are extracted, it could be hard to find good routes, due to the fact that the distance between the remaining piles are long. By leaving piles near the pickup point to the end makes it easier to find good combinations of piles in the end.

5.2. Column generation

Column generation is a technique where columns (in our case routes) to a linear programming (LP) model is generated dynamically based on dual information from the current LP solution, see e.g. Desrosiers et al. [2]. In our case we solve the LP relaxation of the problem [P]. To generate a new column is normally an optimization problem itself. The difficulty depends on the actual application. Here columns with a negative reduced cost is constructed in each iteration. The process terminates when no further columns with negative reduced cost can be found.

In our case it turns out that the subproblem i.e. to find a new route is equivalent to a price collecting TSP problem, see e.g. Fischetti and Toth [3]. This problem is NP hard and we have so far chosen to use heuristics to solve it. The approach is to use the routes obtained from the heuristic as an initial set of columns. Another set of elementary columns is also used. An elementary column is simply a route where the forwarder drives out and picks up only one pile. Obviously we have as many elementary routes as we have piles.

To generate new columns using the current dual information we proceed as follows. There is one dual variable associated with each pile and they reflect the potential reduction of total time if that specific pile where selected in a route. We sort all piles in order of a combination of the dual values and distances and then use two different techniques to combine piles into routes. The first one is based on random generation where the dual values controls the probabilities. The second is based on an insertion technique where piles are dynamically included in a route. If any such route gives a negative reduced cost we include the route into the LP model. Once a specified number of columns are generated or a maximum number of tries are performed we resolve the LP problem to obtain new dual values. This process is repeated until no more columns with negative reduced cost are found. The column generation approach can be illustrated as the flow-chart given in Figure 9.

![Flow-chart](https://example.com/column-generation-flow-chart.png)

**Figure 9:** Main steps in the column generation.

5.3. Integer solutions

A solution to an LP problem is generally a fractional solution, i.e. variables have values in the interval between zero and one. To construct an integer solution we can use a branch and bound method. The general idea is to build a search tree that represents an implicit enumeration of the possible solutions. In each new node in the tree we have new restrictions on some of the
variables. If one can accept an integer solution that is not optimal, but still acceptable, there are a number of available options. In this project we use an intuitive approach that is quite simple. The method we use is called integer allocation. The idea is to gradually force the solution to be integral by adding new constraints to the variables. It can be viewed as a branch and bound approach where we perform a depth first search and when we find the first integer solution we terminate.

6. Numerical results

6.1. Case study

The Swedish company MoDo AB is an integrated forest industry company with forest holdings, sawing industry and pulp- and paper industry. Eight million cubic meter of wood is consumed by the MoDo industries each year. About one third of the volume comes from company forests and half of it is bought from a large number of private forest owners. The rest is imported, mainly from Russia, Estonia and Latvia. Half of the procured volume is harvested in field operations managed by any of MoDo’s six different forestry regions.

The test area is located in the Norrköping region which is the one furthest to the south. Within it about 390,000 cubic meter, of eight different assortments, is harvested annually. This is done with a total of eighteen harvest machines; nine harvesters and nine forwarders. The average forwarding distance for MoDo’s operation in this district is approximately 520 meters.

The harvest area which we used as case study is a relatively small area and has 408 log piles. The number of different assortments is five. The number of road points collected is 234. The distribution of piles among the assortments is given in Table 6.

All routines that are developed are written in C. Some routines are also written in MapBasic to display routes and information in the MapInfo system.

Table 6: The number of piles and average size for each of the five assortments.

<table>
<thead>
<tr>
<th>No.</th>
<th>Assortment</th>
<th>No. of piles</th>
<th>Avg. No. of logs in a pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>spruce-sawlogs</td>
<td>103</td>
<td>6.3</td>
</tr>
<tr>
<td>2</td>
<td>birch-pulpwood</td>
<td>80</td>
<td>15.0</td>
</tr>
<tr>
<td>3</td>
<td>pine-sawlogs</td>
<td>32</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>spruce-pulpwood</td>
<td>152</td>
<td>16.8</td>
</tr>
<tr>
<td>5</td>
<td>pine-pulpwood</td>
<td>41</td>
<td>4.9</td>
</tr>
</tbody>
</table>

6.2. Heuristic

For the heuristic we have developed 22 different strategies. That is, we get 22 solutions to the problem. To find the solutions takes 95 seconds which makes an average of 4.3 seconds per solution. In Table 7 we present the ten best solutions when the heuristic is applied. In column “Test 1” we use a strategy where we start from the far end of the harvest area, as seen from the pick up point. In all tests we only allowed entire piles to be picked up. The total number of routes used was 53 for the best case which gives an average of 7.7 piles in each route. As can be seen, there is little difference between the ten best. We can easily modify this to try the opposite tactic. In other words: we start to build routes closest to the pickup point. The ten best results from the second test are given in column “Test 2”. From the results, we can see that there are relatively small differences between the two tactics.

<table>
<thead>
<tr>
<th>Order</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1444.56</td>
<td>1431.81</td>
</tr>
<tr>
<td>2</td>
<td>1450.66</td>
<td>1445.80</td>
</tr>
<tr>
<td>3</td>
<td>1451.70</td>
<td>1446.11</td>
</tr>
<tr>
<td>4</td>
<td>1452.31</td>
<td>1454.30</td>
</tr>
<tr>
<td>5</td>
<td>1452.73</td>
<td>1454.82</td>
</tr>
<tr>
<td>6</td>
<td>1453.97</td>
<td>1455.43</td>
</tr>
<tr>
<td>7</td>
<td>1455.96</td>
<td>1458.00</td>
</tr>
<tr>
<td>8</td>
<td>1456.89</td>
<td>1463.48</td>
</tr>
<tr>
<td>9</td>
<td>1457.06</td>
<td>1463.56</td>
</tr>
<tr>
<td>10</td>
<td>1457.22</td>
<td>1464.63</td>
</tr>
</tbody>
</table>

An example of a route found is given in Figure 10. Note that the route does not follow the straight line given in the figure. The straight lines are used to show which piles to be picked up in the route. The forwarder follows the roads.

The MapInfo system can also view information associated with the routes. In Figure 11 we give an example of a route where we also have an information box with 1D numbers, the number of assortments, assortments, the number of piles, driving time, loading time and unloading time.

6.3. Solutions with column generation and integer allocation

When we use column generation we start by using the columns found by the heuristics. We have tested several combinations of the number of iterations and
the number of columns returned in every iteration. As an example. When we applied 20 column generations iterations and generated 35 columns in each we found an LP value of 1387.87. The computing time was about 4 minutes. The final value after integer allocation was applied was 1412.74. By using different combination of the heuristics to construct routes we found final values in the range 1402-1423. Corresponding solution times were in the range 8-19 minutes.

The typical behaviour of the column generation and integer allocation is illustrated in Figure 12. In this figure we see that the LP value decreases until about iteration 25 where the final LP value is found. Then the approach starts to fix variables A fixation directly increases the objective value. As the column generation is reapplied, the LP value decreases until the optimal LP value is found again. This is repeated until all variables have value 0 or 1. Towards the end of the process when many routes are fixed there are small possibilities to find good routes among the piles that are not included in routes fixed to 1. The objective value increases much faster with new fixations in this case.

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To make a test with an increased number of assortments we divided one assortment into two assortments (different qualities). The corresponding ten best results obtained by the heuristic is given in Table 8. The difference between the best solutions in the two test cases is 72.1 minutes. With an average running cost of about $90 per hour we can easily measure the direct increased cost. This number could then be used as a very valuable basis in negotiations between the forest owners and the company responsible for the harvesting. It is more difficult to measure additional cost for being delayed a certain time. It is however, very valuable to be able to give very precise estimates on total extraction times.

Table 8: The ten best results obtained from different strategies in the case we have one additional assortment.

<table>
<thead>
<tr>
<th>Order</th>
<th>Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1503.93</td>
</tr>
<tr>
<td>2</td>
<td>1504.97</td>
</tr>
<tr>
<td>3</td>
<td>1506.98</td>
</tr>
<tr>
<td>4</td>
<td>1507.50</td>
</tr>
<tr>
<td>5</td>
<td>1507.87</td>
</tr>
<tr>
<td>6</td>
<td>1510.34</td>
</tr>
<tr>
<td>7</td>
<td>1512.85</td>
</tr>
<tr>
<td>8</td>
<td>1514.70</td>
</tr>
<tr>
<td>9</td>
<td>1515.18</td>
</tr>
<tr>
<td>10</td>
<td>1517.03</td>
</tr>
</tbody>
</table>
7. Extensions

An interesting scenario is that there may be a lack of a particular assortment or a certain amount is required to be available at the harvesting point at a particular time. This will happen more often as saw- and pulp-mills increase their requirements on a steady inflow and more precise delivery times. This aspect gives rise to so-called time window constraints. We introduce the following additional notations:

- \( T \) = number of time periods.
- \( nk \) = number of assortments.
- \( g_t \) = length of time period \( t \).
- \( l(k) \) = Index set defining piles of assortment \( k \).
- \( d_{kt} \) = demand of assortment \( k \) in time period \( t \).
- \( x_{jt} \) = \( 1 \) if forwarder drives route \( j \) in time period \( t \), \( 0 \) otherwise.

The demand of different assortments are of course limited to the actual amount available. The modified model can then be stated as follows.

\[
\text{max} \quad \sum_{j=1}^{n_{tot}} \sum_{t=1}^{T} c_{jt} x_{jt} \\
\text{s.t.} \quad \sum_{j=1}^{n_{tot}} \sum_{t=1}^{T} a_{jt} x_{jt} \geq b_i, \quad i = 1, \ldots, m \\
\quad \sum_{i \in l(k)} \sum_{j=1}^{n_{tot}} a_{ij} x_{jt} \geq d_{kt}, \quad k = 1, \ldots, nk, \quad t = 1, \ldots, T \\
\quad \sum_{j=1}^{n_{tot}} c_{jt} x_{jt} \leq g_t, \quad t = 1, \ldots, T \\
\quad x_{jt} \in \{0, 1\}, \quad j = 1, \ldots, n_{tot}, \quad t = 1, \ldots, T.
\]

The additional constraints imposed are the actual demand of different assortments in different time periods. It would typically be few such constraints. We also need constraints stating that the total time of routes in each time period can not exceed the actual length of the time period.

Another interesting extension is to consider the possibility to use two pick up points. This would be possible in the case when there are two forestry roads adjacent to the harvest area or when the harvest area is parallel to a forest road at a relatively long distance.

8. Concluding remarks

We have suggested a system where we integrate GIS and OR techniques to assist drivers and planners of the extraction of logs from harvest areas. The system uses a GPS to collect information about logpiles and routing network used by the forwarder. OR techniques is then used to find the best possible routes. The system has many advantages. It can be used as an operative tool for the driver to find high quality routes and always have exact information about the current situation. It can also be used as a planning tool to compute additional costs if additional assortments are to be cut. It also gives the planner a larger flexibility as he always know the current availibility of all assortments at all harvest areas. It is also possible to use the system as a simulation tool to test different scenarios and strategies to improve the extraction operations.

There are several aspects that can be further studied. The route generation subproblem can be made more efficient applying more advanced methods. The integer allocation has some drawbacks and there are more advanced Branch and Bound principles that can be developed. In a near future we will test the approach on a number of additional case studies.

9. Acknowledgment

We are grateful to MoDo AB for giving us access to the harvest area used in the test case.

References


