RuttOpt – A decision support system for routing of logging trucks

Gert Andersson[1]
email: gert.andersson@skogforsk.se
Patrik Flisberg[1]
email: pafli@mweb.co.za
Phone: +27 21 7124176
Bertil Lidén[1]
email: bertil.liden@skogforsk.se
Mikael Rönnqvist[1,2]
email: Mikael.Ronnqvist@nhh.no

[1]The Forestry Research Institute of Sweden,
SE-75183 Uppsala, Sweden

[2]Norwegian School of Economics and Business Administration,
N-5045 Bergen, Norway

Abstract

We describe the decision support system RuttOpt, which is developed for scheduling logging trucks in the Swedish forest industry. The system is made up of a number of modules. One module is the Swedish road database NVDB which consists of detailed information of all the roads in Sweden. This also includes a tool to compute distances between locations. A second module is an optimization routine that finds a schedule i.e. set of routes for all trucks. This is based on a two phase algorithm where Linear Programming and a standard tabu search method are used. A third module is a database, storing all relevant information. At the heart of the system is a user interface where information and results can be viewed on maps, Gantt schedules and result reports. We also describe the characteristics of the general routing problem in forestry together with a focus on the planning process and systems in use in the Swedish situation. The system RuttOpt has been used in a number of case studies and we describe four of these. The case studies have been made in both forest companies and hauling companies. The cases range from ten to 110 trucks and with a planning horizon ranging from between one and five days. The results show that the system can be used to solve large case studies and that the potential savings are in the range 5-30%.

Keywords:
Decision Support System, Forestry, Routing, Scheduling, Transportation, Planning, OR in Practice

1 Introduction

Many forest companies are aware of the increased efficiency, both economic and environmental which can be achieved through integrated and better planning of their own or subcontracted companies' fleets of trucks. The routing of logging trucks has a tradition of being a manual process performed by transport planners. Each planner is responsible for a small number of trucks and over a specified and limited region. Better planning is achieved using larger regions and a larger truck fleet. However, this larger and more difficult planning problem requires some decision support system (DSS) to handle all the information and provide solutions to the scheduling problem.

The routing problem can be described as follows. There is a supply of different assortments at harvest areas in forests and a demand at industries for assortment groups. An assortment is a combination of species, dimension and quality. An assortment group is a set of assortments that means that several assortments can be used to satisfy a demand. The volumes of an assortment at a harvest area may vary from a fraction of a truckload to many truckloads. There are time windows or opening hours at both industries and harvest areas for the unloading and loading respectively. Demand at an industry is typically given on a weekly basis, whereas routes have to be found on a daily basis. The routing problem is a pickup and delivery problem where it may be necessary to pickup several small piles of supplies in order to get a full truckload. Each truck has a given home base and working hours. Most trucks change drivers at least once during the day at a specified change-over location. Trucks may be equipped with their own cranes or require the presence of a loader for loading and unloading.

Besides it being a very difficult planning problem, there are additional complicating factors when developing a DSS for routing of logging trucks. There is a need to get detailed information about roads, for example, about distances, speed limits, and road quality. A second factor has been the need to have access to accurate information about truck availability, demand, and in particular, supply. A third factor is to have quick and robust methods that can assist the planner with detailed routes that are cost effective for the entire fleet. A fourth factor is the actual planning process and how it fits within the company's organisation and can be integrated with external companies/ organisations. These factors have been included in a system called RuttOpt which is a DSS developed during the years 2003-2007 by the Forestry Research Institute of Sweden (Skogforsk) together with a number of participating forest and consulting companies.

Many methods have been proposed for the vehicle routing problem (VRP). However, due to the fact that it is a hard combinatorial problem, exact methods perform poorly for real size problems and this motivates the development of meta heuristics. Moreover, there are many versions of VRP and these depend on a variety of aspects, such as, pickup and delivery, backhauling, multiple depots, heterogeneous fleet, multiple routes per vehicle etc. For general surveys of VRP we refer to Cordeau et al. (2002) and Gendreau et al. (2002). The routing problem for logging trucks has some particular aspects that makes it different from a standard VRP besides it being a combination of the different aspects mentioned above. There are generally more supply volumes than actual demand volumes. Furthermore, there is generally no specified linkage that states that a specific supply should be transported to a specific demand. Typically, all supplies can be transported to all demands providing the correctness of the assortments. The demand typically ranges over several days but with lower and upper limits for each day. This implies an integration between days or time periods and the problem becomes a multi period problem.

An early DSS for logging trucks is ASICAM (Weintraub et al. , 1996) which is used by several forest companies in Chile and other South American countries. It produces a schedule for one day by a simulation based heuristic that assigns transport orders (combination of pickup and delivery) to trucks in a moving time horizon. A decentralized system is Åkarweb (Eriksson and Rönnqvist, 2003). Åkarweb is a web based system that each day computes potential transport orders by solving a Linear Programming (LP) based backhauling problem. Backhauling is to find two direct flows between supply and demand (where the truck drives loaded in one direction and empty back) and combining them into a backhaul route where the empty driving is reduced. From the potential transport orders, transport managers select transport orders to combine them into routes. In Gingras et al. (2006) a system named MaxTour for forest routing in Quebec, Canada, is described. This system establishes routes based on the classical heuristic by Clarke and Wright by combining predefined loads in origin-destination pairs. There are large differences between countries in how the decision process takes place. This is a result of several factors including company management, organisation of trucks, information available, and the use of geographical information systems.

The main purpose of this paper is to describe an advanced DSS for forestry and show its usage on a set of case studies from Swedish forest companies. With the development of road databases, GIS, and improved real time information systems at companies, the development of sophisticated DSS based on Operations Research (OR) methods is possible. The aim of the development of RuttOpt has been to build a DSS platform that can be used directly at companies. The system uses the National Road database for information about the Swedish forest road network. A customized database is used to store information about supply, demand, home bases, trucks, and costs. The system ArcMap is used as GIS to view all data and routes and built-in modules are used to view schedules. The system RuttOpt has been developed for the Swedish situation and we will focus on this. However, many parts of the system can be modified for other situations. The system has been tested in several case studies from Swedish forest companies. This includes a case with 110 trucks, 113 demand points and 2,531 supply points. When we formulate this case into a model over five days, it corresponds to more than 3,800 customers in a standard VRP formulation.

Two research contributions of this paper are a detailed description of basic route planning within forestry planning and how the planning is done in Sweden. A third contribution is that we have developed a system that fits in the planning process and can easily be implemented at other companies. A fourth contribution is that we have showed that it works on real problems in four different case studies.

The outline of the paper is as follows. In Section 2 we describe the routing problem for logging trucks in forestry together with existing methods. In Section 3 we describe the planning process, systems, and organisations influencing the transportation. In Section 4 we describe the RuttOpt system. In Section 5 we describe four case studies where RuttOpt has been used. In Section 6 we make some concluding remarks.

2 Problem description

2.1 Routing of logging trucks

Transportation planning is one part of the forest supply chain (Rönnqvist, 2003) and the routing of logging trucks is one part of the transportation planning. It is an operative planning problem and as such, should follow plans found in a upper level tactical problem. In Figure 1 we provide three linked planning problems.

The destination problem is generally solved using a monthly planning period. Here, catchment areas for each combination of industry and assortment is determined. These can be found by solving a flow problem where the flows of different assortments between harvest areas and industries are determined. The solution can be used for example to distribute work fairly between haulage companies. In Forsberg et al. (2005) a system for a tactical problem is described. Here, train and ship transportation and backhaul planning are included. The destination planning is often done centrally by a forest company with delivery responsibilities for industries. Once a des-

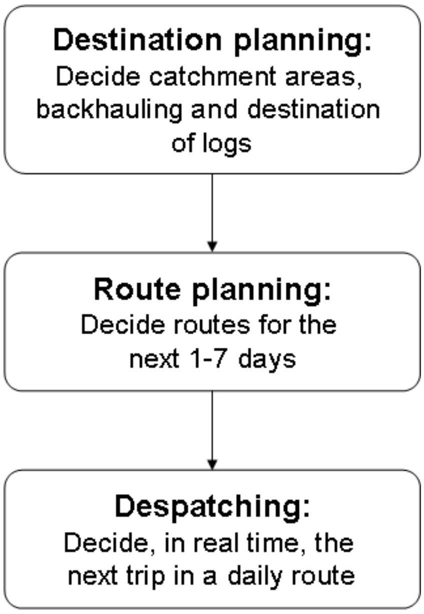

Figure 1: Different levels for transportation planning.

tination plan has been found, transport orders are distributed to a number of transporters. Transporters may be a combination of a larger independent transport company, a transport organisation within the forest company, or individual hauliers with one or a few trucks. Each transporter typically operates within a specific area. The distribution of transport orders together with decentralized planning, of course imposes a limitation to how good the routes can become.

The routing consists of deciding a cost effective schedule, one route for each truck, to match demand with supply. Several models and methods have been developed for the scheduling of logging trucks in the literature. In Weintraub et al. (1996), a combination of simulation and heuristics is used to sequentially construct routes over a full day. In Palmgren et al. (2003) a column based routing model is used and solved using Branch & Price. The pricing process (column generation) is based on a pre-generated pool of columns. This pool is found by a heuristic enumeration which in turn, uses the result of a LP based flow problem. In Palmgren et al. (2004), the same approach is used but the pool is extended by resolving the LP problem several times. Murphy (2003) formulates a general integer programming model for the routing model but uses it only for tactical long term planning. Gronalt and Hirsch (2005) describe a tabu search method where a set of fixed transports are to be performed. Time windows and multiple depots are included in the formulation. In Flisberg et al. (2007) the method used in RuttOpt is described. This method will be discussed more in Section 4.

Dispatching involves deciding about routes continuously during the day based on real time events such as queuing, bad weather, truck break down etc. In Rönnqvist and Ryan (1995) a solution method for dispatching is described. The method establishes solutions for a fleet of trucks within a few seconds. It is based on recursively solving a column based model whenever changes in data occur. In Rönnqvist et al. (1998) a similar dispatch problem is studied with a method based on recursively solving assignment problems.

2.2 Route information

Detailed information is needed for the planning process. Parts of the description in the following sections are based on Flisberg et al (2007). In Figure 2, we start to describe the actual routing to show a typical route performed by a logging truck during one day. Information about a route is given in Table 1. We note that it is a pickup and delivery problem. A truckload for a delivery to a customer may be picked up at several supply points. There may also be several pickups at the same supply point during a day. In the example, there is also a change of drivers.

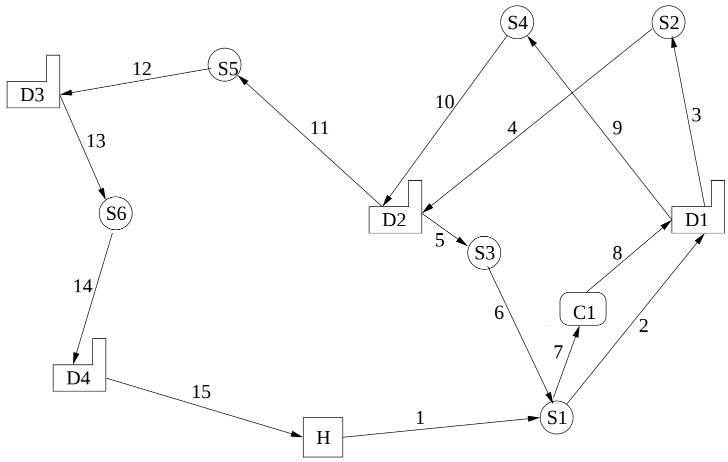

Figure 2: Example of a daily route for a logging truck. Driving between locations is numbered from 1 to 15.

2.3 Routing components

Supply and assortments

At each harvest area, a number of products or assortments are produced. An *assortment* is defined by species, for example Spruce, Birch or Pine, together with dimensions and quality. Logs with a smaller diameter are typically

Arc	Time	From	Time	To	Operation	Assortment	Volume
1	06.00	H	06.45	S1	Drive to area S1	—	—
	06.45	S1	07.00	S1	Load logs at S1	Spruce sawlogs	40 ton
2	07.00	S1	07.50	D1	Drive to mill D1	Spruce sawlogs	40 ton
	07.50	D1	07.10	D1	Unload logs at D1	Spruce sawlogs	40 ton
3	07.10	D1	08.00	S2	Drive to area S2	—	—
	08.00	S2	08.30	S2	Load logs at S2	Spruce pulplogs	40 ton
4	08.30	S2	09.50	D2	Drive to mill D2	Spruce pulplogs	40 ton
	09.50	D2	10.00	D2	Unload logs at D2	Spruce pulplogs	40 ton
5	10.00	D2	11.00	S3	Drive to area S3	—	—
	11.00	S3	11.20	S3	Load logs at S3	Spruce sawlogs	25 ton
6	11.20	S3	11.40	S1	Drive to area S1	Spruce sawlogs	25 ton
	11.40	S1	12.00	S1	Load logs at S1	Spruce sawlogs	15 ton
7	12.00	S1	12.30	C1	Drive to node C1	Spruce sawlogs	40 ton
	12.30	C1	12.40	C1	Change driver	Spruce sawlogs	40 ton
8	12.40	C1	13.30	D1	Drive to mill D1	Spruce sawlogs	40 ton
	13.30	D1	13.50	D1	Unload logs at D1	Spruce sawlogs	40 ton
9	13.50	D1	15.00	S4	Drive to area S4	—	—
	15.00	S4	15.20	S4	Load logs at S4	Spruce pulplogs	20 ton
	15.20	S4	15.40	S4	Load logs at S4	Pine pulplogs	20 ton
10	15.40	S4	17.00	D2	Drive to mill D2	Spruce/Pine pulplogs	40 ton
	17.00	D2	17.20	D2	Unload logs at D2	Spruce/Pine pulplogs	40 ton
11	17.20	D2	18.40	S5	Drive to area S5	—	—
	18.40	S5	19.10	S5	Load logs at S5	Spruce sawlogs	40 ton
12	19.10	S5	20.00	D3	Drive to mill D3	Spruce sawlogs	40 ton
	20.00	D3	20.30	D3	Unload logs at D3	Spruce sawlogs	40 ton
13	20.30	D3	21.20	S6	Drive to area S6	—	—
	21.20	S6	22.00	S6	Load logs at S6	Pine pulplogs	40 ton
14	22.00	S6	22.50	D4	Drive to mill D4	Pine pulplogs	40 ton
	22.50	D4	23.10	D4	Unload logs at D4	Pine pulplogs	40 ton
15	23.10	D4	23.40	H	Drive home	—	—

Table 1: Information of a typical route during one day related to the route in Figure 2.

pulplogs and logs with larger diameter are classified into different sawlogs. In some cases, there are specific requirements. An example is when a saw mill orders a specific length and/ or diameter and quality. A pile of logs of each assortment is put adjacent to a forest road. Each harvest area is defined by a geographical node. As there are several assortments at each harvest area, there are several piles and therefore we define a *supply point* as a combination of a geographical node and an assortment. Information connected to each supply point is a geographical location, assortment, and a volume. Production may occur for several days or weeks at a harvest area and logs are continuously being transported to mills. Once the harvesting is finished there is a need to empty the area within a certain time as the quality of logs decreases with time. This can be controlled by imposing a cost or penalty for not removing the logs. A harvest area is often available 24 hours a day. However, trucks without a crane need an independent loader for the loading. A loader requires staff and is available within given working hours. A harvest area therefore has two time windows. The general availability (for all trucks) and the loader availability. Beside harvest areas, supply points can also be defined, as illustrated in Figure 3, as storage terminals, harbours, and train terminals.

Figure 3: Illustration of potential supply and demand points.

Demand and assortment groups

A *demand point* is defined as a customer order at an industry i.e. saw-, pulp-, paper mill, heating plant, combined heating and power plant, or a terminal. A terminal can be either a demand point (if a stock should be built up at the terminal for future demand) or a supply point (if there is a stock at the terminal). A customer order is defined by an *assortment group*, a volume, and a time period. An assortment group can be one or several assortments. This means, for example, that both Spruce and Pine pulplogs might be used to satisfy a certain demand. In case there are limits on the proportions of different assortments in an order it could be split up into several demand points. For example, if an order is for 1000 tons and it needs to be at least 30% of Spruce and Pine each, then we define three demand points; one for

300 tons of Spruce, one for 300 tons of Pine, and one for 400 tons of combined Spruce and Pine. There are given opening hours at each demand point. If it is a paper or pulp mill, the time window is often very wide, often 24 hours a day, but for a small sawmill it may only be a few hours per day or week. The demand is often given on a weekly basis but it needs to be divided into different days. In order to have a flexibility we do not have a fixed demand per day instead there is a minimum and maximum accumulated volume per day. This is illustrated in Figure 4 where the accumulated demand is given for five days.

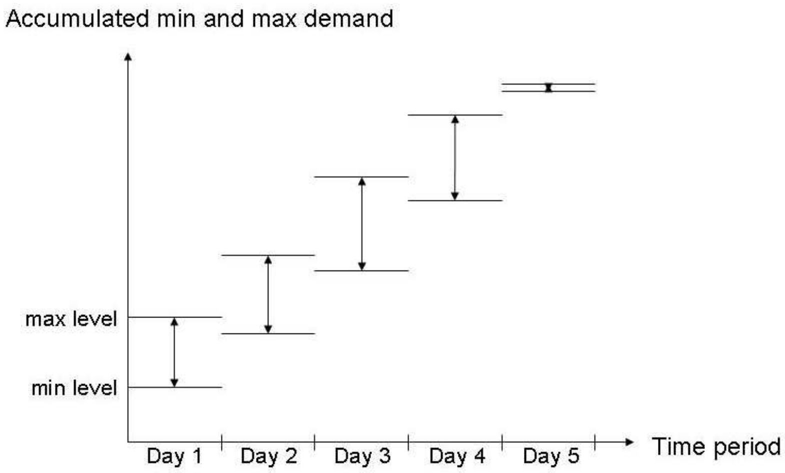

Figure 4: Example of a demand profile over five days.

Trucks and drivers

There are two types of logging trucks; with and without a crane. Figure 5 illustrates the two types of trucks. With a crane, there is no need for a loader at the supply point. The loading capacity without a crane is about 40 tons and with a crane three tons less i.e. 37 tons. Trucks belong to a haulier that owns one or several trucks. The working time for a truck is determined by the number of drivers during the day. A truck with three drivers can operate 24 hours each day whereas a truck with one driver is limited to about 10 hours. In the case of several drivers, these change at specified change-over locations. Each truck is located at a home base from where it generally starts and ends each day. In general we have different costs for loaded and unloaded driving and working hours. The working hours are specified for each truck in detailed schedules.

Figure 5: Examples of a standard truck without a crane (left) and with a crane (right). Gross vehicle weight is 60 tons and tare weight for a truck without crane is approximately 17-20 tons. A truck with a crane weighs about three tons more.

Loaders

In the case of trucks without a crane, there is a need for loaders. A loader is illustrated in Figure 6. Loaders typically operate over several harvest areas and have limited working hours. It is a separate problem to schedule the loaders between the harvest areas. In our case, we assume that such a schedule is given.

Figure 6: Examples of a loader.

Distances and geographical nodes

There are four different types of geographical nodes: supply points, demand points, change-over nodes, and home bases. In Figure 7 we have a map from a case study with related nodes. One important aspect of the geographical nodes is that it is possibility to compute distances and traveling times between all pairs of nodes. We make use of the Swedish national road database NVDB which has detailed information of all the roads in Sweden.

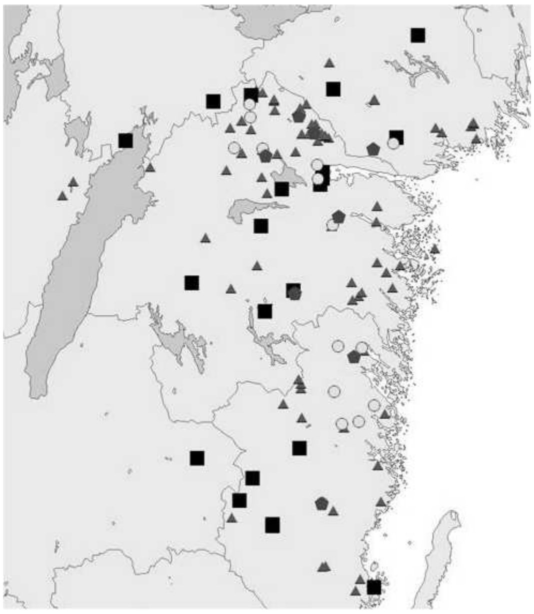

Figure 7: A map from a case study showing the distribution of geographical nodes (demand points: squares, supply points: triangles, home bases: pentagons, change-over nodes: circles).

Objective and costs

The objective is to find the most efficient plan for the entire fleet of trucks. We want to find the minimum cost while satisfying the demand. In order to obtain a model which is both flexible and robust we have included a set of costs and priorities in the objective. The most obvious cost is the actual routing cost. This cost is defined by a unit distance cost for the loaded and unloaded distance traveled. In addition, we have a cost associated with the working time, that is, the time the truck is in operation. There may be situations when it is not possible to satisfy the demand. Then we have included a unit volume penalty for not satisfying the demand.

There may also be situations when a demand point has a lower demand limit but would like to have more if possible. A demand point can then specify a bonus value for each ton of logs supplied. Often there is a need to empty all piles of logs from a harvest area and in order to control this, we have a bonus for each ton removed from the supply point. It is however only applied to supply points that the planner wants to empty.

3 Transportation planning

There are differences in the planning processes and standards between countries and between companies. The RuttOpt system has been developed for the Swedish situation and we limit ourselves to describing this situation. However, the Swedish situation has much in common with other situations and it is easy to replace parts of the system with another situation.

3.1 Planning process

A majority of the transportation work is carried out by small hauliers or transporters, often with only one or two trucks. The transporters often collaborate in larger associations. These associations take on work from the forest companies and distribute the work among their members. The larger forest companies have different models for purchasing transport services. The forest companies work with both small and large transporters. The transporters often work with weekly and monthly quotas agreed with the forest company.

In the tactical and the weekly operative planning, either the forest company or the transporter has the planning responsibility. Each transporter has a responsibility for a limited geographical area. Within this area, the transporter takes care of all transportation work. Collaboration with other transporters in order to create efficient backhauling routes is done on an ad hoc manner and using personal relations. Decisions on the daily routing is generally decided by the individual truck driver within the limit of the weekly quota. In some, but few, cases, the driver follows a given schedule.

The transport planner creates a transport order when the harvesting has been done and forwarding operations have started. This transport order provides the destination of each assortment at the harvest area. It is given to the transporter responsible for the area to which the harvest area belongs. The transport order is communicated via telephone, fax, or IT systems that are used at the drivers' home offices or directly to on-board computers in the trucks. There are several different IT systems in use which will be described in more detail. The transport agreements between transporters and forest companies are based on the fact that trucks drive loaded from the supply point to demand point and empty in the other direction. If a backhauling route is used, there is a saving based on the decreased empty driving. The savings are split according to special rules e.g. 50% each.

3.2 Related organisations and standards

To administrate all information about roundwood measurement and invoicing, an independent organisation called "Skogsbrukets datacentral" (SDC) was established in 1961. SDC is an economic association and is owned by the Swedish forest companies. SDC is an information hub and deals with approximately 450 measurement installations (data capture units) at industries, sawmills, and energy production plants. About 700 harvesters and 700 forwarders report production figures to SDC. This corresponds to about 50% of the total fleet of harvesters and forwarders. The production figures can also be used to update the actual road storage volumes in internal IT systems at the forest companies. About 125,000 timber suppliers (forest owners) receive documentation of their wood sales. Approximately 140 million cubic meters is handled in SDC systems. About 130 companies and 2,000 users are integrated with SDC through their IT-systems.

The measurement of roundwood is regulated by a special law. In principle, all roundwood is measured at the receiving industry. Three independent associations are responsible for the activities in three geographical regions. All measurement units send information one or several times per day to SDC. The coordinates of the harvest area are registered together with the volume and assortment.

To support the activities at SDC, a system called VIOL is used. The Swedish acronym is "roundwood on-line". All major buyers and sellers of roundwood use the system for the business and all deliveries in the chain from forests to industries are registered. The VIOL system includes standardized codes for assortments and demand points. Standardized codes also enable backhauling and exchange of wood between companies.

At the request of the forest companies and forest owners' association, SDC is responsible for maintaining SNVDB, the Forestry National Road database. The national road database will be described as a component of the system RuttOpt.

StanForD is an abbreviation for "Standard for Forestry Data and Communication". The on-board merchandising or bucking computer was introduced on Swedish logging machines in the mid-1980s. Skogforsk is responsible for the development and maintenance of the standard. The standard was agreed upon in 1987 and was further developed during the 1990s. StanForD mainly comprises a data standard and a file-structure standard for the harvesting operations. Today, StanForD is used in several countries and de-facto constitutes a standard in Europe, even though it has not been awarded any official status.

The networks available for wireless communications differ in coverage and capacity. The Mobitex network in 80MHz shows the best coverage, but the data throughput is rather low, around 1 kbps (kilobit per second). One of the three available GSM-networks in Sweden will cover 90% of the country from the beginning of 2008. A special technology called EDGE will also be implemented. It will allow data throughput of up till 200 kbps compared with up to 48 kbps for GSM/GPRS today. A new network using a technology called CDMA450 will be rolled out in 2007-2008. This network will cover at least 80% of the area in each county and will allow data throughput of approximately 500 kbps. In Figure 8, we describe the coverage today of the GSM system and the planned coverage of the CDMA450 in 2009. All speeds for data communication concern the so-called downlink, i.e. the speed when downloading data in the mobil device. Uploading data from the mobil device is lower but at least 50% of the downloading speed. With this increased coverage and data capacity there will be new opportunities for web-based applications in the trucks, forwarders, and harvesters.

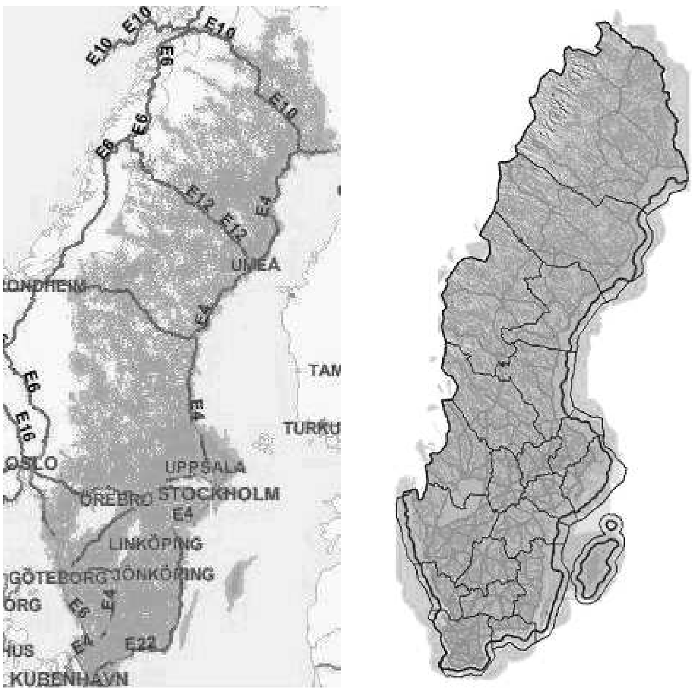

Figure 8: Left figure: GSM coverage (grey) March 2007 (source: www.telia.se). Right figure: estimated coverage of the CDMA450 in 2009 (source: SAAB Communications).

3.3 Planning systems in use

In Sweden there are four major DSS in forestry transportation in use. These are KOLA, SMART, TROMB and Åkarweb. The primary purpose of these systems is to administer and communicate transport orders between company central systems, home offices, and trucks. An important part of the systems are standardized on-board computers equipped with GPS based navigation system. Planning support for routing is limited. Together, the four systems handle about 700 logging trucks out of a total of 1,400 in Sweden.

The system KOLA (Swedish: KOmmunikation LAstbil) has been developed by the forest association Södra and the wood procurement company Sydved (Ekstrand and Skutin, 2005 and Kallin, 2007). It has a web-based user interface where the driver connects to a server through the on-board computer or a PC at home where information about transport orders, road side inventory, and forwarding reports are stored. When the driver has finished loading at a supply point, the driver reports to the receiving industry about the load and updates the roadside inventory to the system. The communication between truck and office is carried out by GSM/GPRS. KOLA has no support to generate routes. KOLA is used by 350 trucks and on-board computers are mounted in 330 of these.

The system SMART (Swedish: Skogsåkarnas MiljöAktiva Rutt- och Transportledningsssystem) has been developed by the transporter Skogsåkarna with the support of some larger customers (forest companies) (Ekstrand and Skutin, 2005 and Forslund, 2007). In SMART, Skogsåkarna receives the monthly quotas on demand and can continuously do transport planning. Each day, production data from customers' forwarders is received into the system. SMART consists of two office modules for transport requests and transport planning and one mobile module to receive transport orders and report on transports performed. The mobile application includes digitized maps, a mobile internet, and GPS positioning. The transport request module handles information about delivery plans, supply and demand points, e.g., opening hours and coordinates. In the mobile module, each driver reports on roadside inventories and transports completed. The transport module in SMART has a support developed for route planning. However, its usage is limited. SMART is used by 170 trucks and on-board computers are mounted in 130 of these.

The system TROMB (Swedish: Transport Och Mobil Beordring) has been developed by the transporter VSV (Ekstrand and Skutin, 2005 and Parklund, 2007). It is used for transportation planning, creating transport orders, follow up, mobile communication, and navigation support. It consists of an office module and a vehicle module. In the office module, the planner administrates transport orders and make plans. The planner can view roadside inventory and communicate with drivers via fax, sms, and E-mail using either Mobitex or GSM/GPRS. TROMB has no support to generate routes. TROMB is used by 100 trucks and on-board computers are mounted in 50 of these.

The system Åkarweb has been developed by the forest company Holmen Skog (Eriksson and Rönnqvist, 2003 and Johansson, 2007). The main purpose of the system is to provide a support for co-ordination and interaction between the transport managers at the companies associated with Holmen Skog. It has a map-system where the users can view roadside inventory, demand at industries, and the geographical road network. Data for supply and demand (reported and measured) is updated continuously by forwarders. Each user, generally a transport manager, can view data that relates to his/ hers transportation district/ organisation. Åkarweb has a support to generate bachauling routes in order to improve the route planning. Each morning, potential backhaul routes are generated. These can be used by the transport planners to manually improve the route plan together with other transporters. Åkarweb is currently used by 50 transporters associated with Holmen, and represents about 80 trucks. On-board computers are mounted in 10 of these.

4 System RuttOpt

4.1 System overview

Route planning includes a great deal of work preparing data and interpreting results. Those actions are very time-consuming if done manually. It is also hard to control accuracy and find errors in the data. The RuttOpt system makes it easier to handle data and interpret results in a semi-automatic way. The time used for an analysis is considerably decreased when using the system. Basically, the process to use RuttOpt has four separate elements:

1. Collecting data
2. Pre-processing and set up of data for optimization
3. Optimization
4. Processing and interpreting the results, report generation

The main components of the system are given in Figure 9. The "Main application" is the central part of the RuttOpt system. This user interface offers different functionality for viewing geographical data and results, report generation and editing the data. The interface uses different modules; the Swedish national road database (NVDB) with detailed information of all roads, a geographical user interface (ESRI ArcView), a database (Microsoft

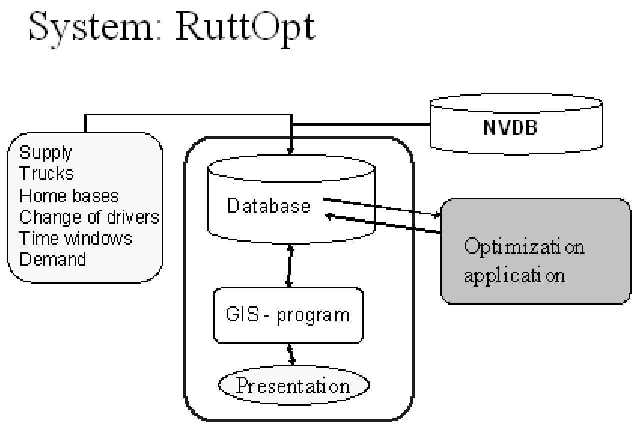

Figure 9: The main components included in the RuttOpt system.

Access) with all case information, and an external route planner communicated through a defined interface. Different solution methods can be used in the route planner as the interface is defined by a set of input/ output files.

4.2 Road database

The Swedish National Road database (NVDB) was developed in a collaboration between the Swedish National Road Administration, the Central Office of the National Land Survey, the Swedish Association of Local Authorities, and the forest industry. The database contains digital information of all Swedish roads; the state road network, the municipal road and street network, and private road networks. All roads, approximately over 500,000 km, are described geometrically, topologically, and with detailed information about each road segment. This includes road manager (owner), road classification, road designation, height restrictions, load bearing obstacles, surface material, width, and traffic regulations. For transportation on forest roads there are also special details about accessibility, turning radius, barriers etc. These details are handled by SDC as an add-on to NVDB thus creating the Forestry National Road database (SNVDB). An illustration of the geographical information is given in Figure 10. For any given user of a national road database, it is important that data is up-to-date. This is handled through data registration at source, i.e. the road manager is responsible for supplying data within his/ her fields of operations. In this way data is registered by a manager with knowledge of the conditions and can ensure continued updating.

Figure 10: The Swedish National Road Database includes all Swedish roads. Here is an illustration of the network around the city of Uppsala.

To calculate the actual distance driven between two locations is not straightforward. The transport agreements are typically not based on the shortest distance. Instead they depend on a combination of attributes such as distance, speed limits, road owner, road width, and road surface. In the system, we can choose a combination of these factors in order to establish a distance table between all pairs of nodes used in the planning process. In practice, we choose a weight for each attribute and these are combined into a single value for each road segment. Those calculations are done in a separate function in the main application. In order to make the shortest path computation fast, a special network is constructed based on the information from NVDB.

When the manual solution was carried out the drivers recorded the traveling time between locations. In Figure 11 we present a comparison of the real measured traveling times and estimations used by RuttOpt. The estimated times are sorted with regards to time. Differences between real and estimated time can be explained by three potential errors, in the road database, the way the choice of roads component works, and in errors in measured (real) travel times. However, the estimated time follows the trend line of the real times and can be regarded as a qualitative description of the transportation times.

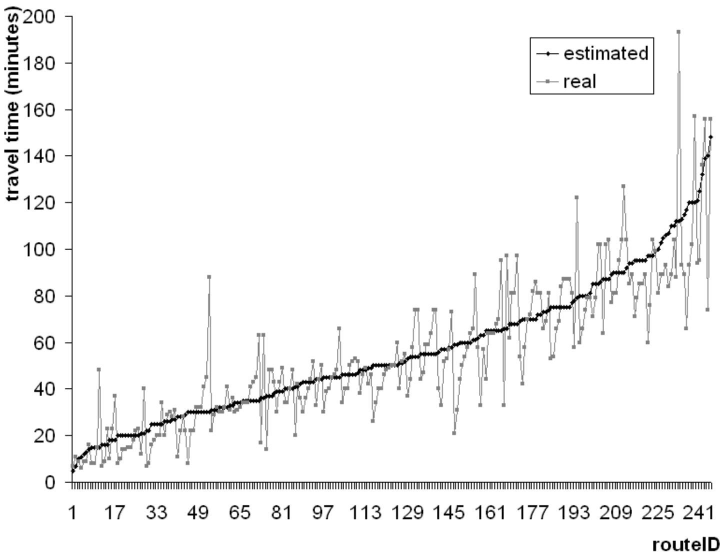

Figure 11: Estimated (black line) versus real (grey and fluctuating line) travel times.

4.3 Internal database

The internal database includes information about the data components described earlier. This data can be changed and checked from the user interface. If a schedule is to be found, a set of structured text input files are generated and made available for the route planner. These files include all the relevant information. One purpose of this text file interface is to easy change between different possible solvers to the RuttOpt system. The data includes:

Geographical nodes coordinates for supply nodes, industries, home-bases and change-over locations, time windows (open)

Truck Type, homebase, priority, working schedule, costs per hour and per km loaded and unloaded, capacity, loading and unloading time, speed for each roadtype

Loader Node availability, time windows (each node), loading and unloading time

Supply node ID, assortment, volume (each time period), priority

Available supply points For each truck the allowed supply points are listed.

Destination For each demand points the allowed supply points are listed.

Demand node ID, assortment group, min and max volume (accumulated per time period)

Unloading Turn-around time (volume measuring and unloading) for each demand point (for each time period)

Assortment/ Group assortment all relations between assortments and group assortments

4.4 Route planner

During the development of the system we have tested different methods in RuttOpt. First, we used methods based on Palmgren et al. (2003) and Palmgren et al. (2004). In these articles, Branch & Price (B&P) methods are used to solve a column (route) based formulation of an easier problem with a one day planning horizon and one truck type (trucks with cranes). The subproblem for finding routes was based on various heuristics. The approach works for smaller instances and shows large savings in comparison with manual solutions. In Palmgren (2005), a modified subproblem was formulated and tested with B&P on a one day case. This is based on the smallest case study in this paper with one time period. However, even with long solution times, the B&P approach failed to find feasible solutions.

In order to solve larger and more general instances, a new solution approach was developed. This is described in detail in Flisberg et al. (2007). The solution approach works in two phases. In the first phase we construct so called *transport nodes*. A transport node describes the possible multiple pickup points and one delivery point for a full truckload. This is done by solving a flow problem using variables for each truck and each combination of supply and demand points each day. Constraints describe demand, supply, and time availability of each truck. This is an LP model which is a relaxed and simplified version of an IP formulation of the full problem. We use transport nodes to describe the change of drivers during a day as well. Given the transport nodes, we can formulate a VRP problem with time windows (VRPTW). In standard VRP terms, a transport node would be equivalent to a customer. In the second stage, we use a well known tabu search method as a basis to combine transport nodes to routes. We utilize the unified tabu search method proposed in Cordeau et al. (2001). However, we have extended the method mainly to enable differences in supply and demand and multiple home bases. We refer to the extended method as EUTSA.

When the data is read by the route planner, a set of preprocessing tests are performed in order to check the data. One example is a basic check that there exists enough supply to fulfill the different demands. Assortments requirement and limitations as to what supply points can be used for a certain demand point, are taken into account. Other examples are that all supply and demand points are associated with existing nodes and that there are distances defined from each supply point to at least one demand point. During the solution process, a debug file is generated in order to detect problem with the data that can more easily be identified during the solution process. One example is if no feasible solution exists to the flow problem. The demand points that can not be fulfilled are then listed in the debug file. Another example is if no truck is allowed to visit a supply point or if the supply point cannot be used to fulfill any demand. Warning messages are then written in the debug file.

In implementing the overall solution algorithm there are a number of special aspects to consider that are not included directly into the solver. However, they may be used in practice. The EUTSA method works on a daily basis and can not be used to determine if a vehicle should pickup a load at the end of one day and deliver it at the beginning of the next day. Instead, this is done in a post-processing routine. The same is true for the change of drivers. In EUTSA, a driver change over is modeled as a separate transport node which means that this operation is done with an unloaded truck. To check if a route can be improved by performing the change over in another transport node but with a loaded truck is also done in a post-processing routine.

4.5 Report generation

Results and debug information from the optimization module is imported back into the main application. From the user interface, different report options are available. One example is Gantt schemes, see Figure 12. It is also possible to get summary reports for each truck regarding e.g. loaded distance, unloaded distance, working hours, waiting time, and total cost. Furthermore, it is possible to view e.g. routes directly in the GIS menus.

5 Case studies and results

We have used RuttOpt in four case studies. Each of the case studies has been done at a different forest company and transporter. They have specific characteristics and are located in different regions of Sweden.

The first case study was done together with Holmen Skog. The main purpose was to develop and test the solution approach and compare this with manual results covering three days. In this case, each vehicle kept a diary for all the

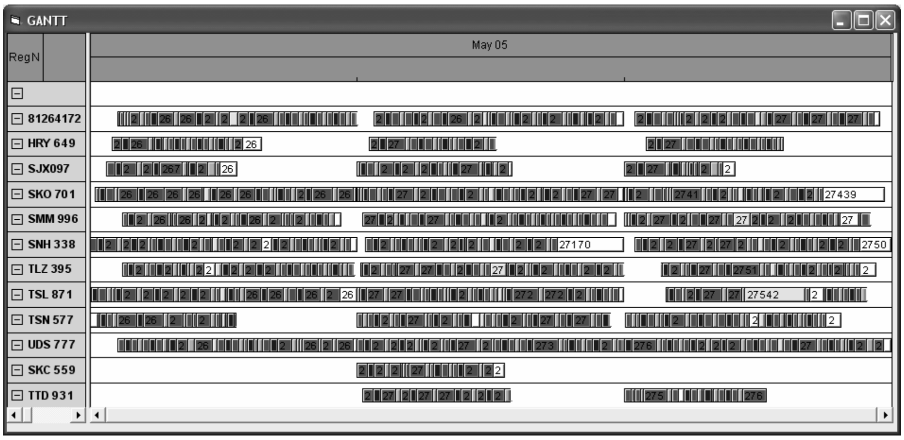

Figure 12: A Gantt scheme for three days covering 12 trucks. Different colors represent different actions. For example, empty run, loading, loaded run, unloading, change of drivers, and breaks.

transports carried out during three days. The available road side inventory at the beginning of day one was recorded and used as overall supply.

The second case study was done with Stora Enso and three haulage companies. In this case, data for five days was collected in co-operation with Skogsåkarna, a large hauling association. Skogsåkarna is responsible for almost all the transports of roundwood in the area concerned. This case is used to analyze the effect of changing planning parameters such as opening hours. A second aim was to test the performance of the proposed solution method for large scale problems.

Skogforsk is running a number of implementation projects in order to test new decision support systems directly at companies. One of these projects is to test RuttOpt in direct operations with two organisations. Cases three and four are done with two companies within this framework. The third case study was done with the forest company SCA Skog. Many of the transports are between the coast and inland and the potential for backhauling is low. In the material, we tested the effect of joining three smaller regions into one large region. The fourth case study was done with VSV which is a transportation and logging company operating in the middle of Sweden. The potential for backhauling is larger here than in case three. We also tested the effect of combining several small areas into one larger area.

Information about the size of the case studies is given in Table 2. We note that the second case, covering 110 trucks over five days, is a very large VRP problem. Cases 1 and 2 are based on actual roadside inventory (with supply larger than demand) whereas cases 3 and 4 have a balance in supply and demand. We have done experiments and analyzed these cases. All experiments have been performed on a standard PC with a Pentium 4, 2.4 GHz processor and 1 GB internal memory.

	Case 1	Case 2	Case 3	Case 4
# trucks/ vehicles	12	110	10	10
# hauliers (transporters)	8	79	3	8
# industries (demand nodes)	22	74	8	19
# demand points	24	113	8	19
# supply nodes	167	665	26	65
# supply points	410	2,531	48	98
# time periods (days)	3	5	3	3
demand volume (tons)	7,511	101,018	4,033	4,440
supply volume (tons)	33,331	261,260	4,033	4,440

Table 2: Information about the case studies.

5.1 Case study 1: Holmen Skog

Holmen Skog manages the Holmen Group's forests, purchases wood from private forest owners and procures wood for Holment́s Swedish units. Every year, Holmen Skog procures more than 11 million cubic metres of wood. Most comes from private forest owners or other Swedish forest companies. The wood is delivered to the Holmen Groupt́s own production units, other forest industry operations, and local sawmills. The case is taken from the Norrköping region and covers 12 trucks. The geographical distribution of nodes for this case study is given in Figure 13.

The data has been collected over a period of three days. The purpose was to test the solution approach and compare this with manual results covering the three days. In this case, each vehicle kept a diary for all the transports carried out during the three days. The available road side inventory at the beginning of day one was recorded and used as overall supply. We have extracted a set of instances to test the performance of the solution approach compared to the manual solution. In Table 3 we give the instances and their characteristics as well as some results. The column "Volume" indicates if the available supply points and their volume is exactly the same ("YES") as the supply points that were visited and the volumes loaded in the manual solution, i.e. the supplied volume for these cases is about the same as the demand volume. The column "Fixed" refers to whether each supply point can only be visited by one or two different trucks ("YES"). The trucks are then restricted to visiting only the same supply points as they did in the manual solution. For each supply point not visited in the manual solution, only one truck is chosen as the allowed truck. The column "Data" shows which

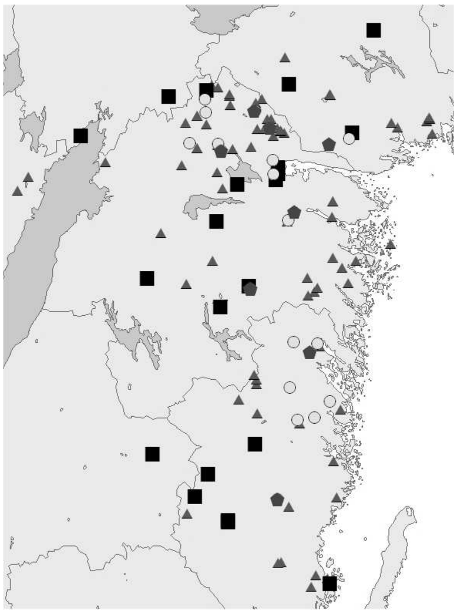

Figure 13: Geographical distribution of nodes for Case study 1 (demand points: squares, supply points: triangles, home bases: pentagons, change-over nodes: circles).

day(s) are extracted. When the days 1-3 are extracted, we solve the problem with three time periods. The solution time is 10 minutes and the number of calls to EUTSA is given as "#iter". The column "#TN" gives the number of transport nodes used. The transportation cost is given for the manual solution (column "Manual") and for the solution from the EUTSA method (column "EUTSA"). The column "%Loaded" refers to the loaded part of the transportation cost for the solution from the EUTSA method. The column "Imp(%)" refers to the improvement in transportation cost when using the EUTSA method compared to the manual.

In the manual solution, some vehicles were loaded late one day, drove home and were only unloaded the next day. These loads are included in the demand in the instances covering three days but not in the other instances since these are generated from the explicit parts of the manual solution for each day. Therefore, the total demand for the instances over a three day period is more than the total demand for the instances of days 1, 2, and 3 added together. Even though there are restrictions, the EUTSA finds considerably better solutions than the manual solutions. Large savings can be made, if trucks are not limited to visiting only some supply points.

Certain supply points might have to be emptied since the maximum time from when a tree is harvested until it has to be transported away from the forest is about 30 days. This can be achieved by setting a high bonus for these supply points. We have simulated this in Case C1-14. The total transporta-

				Transp. cost					
Case	Vol.	Fixed	Data	Manual	EUTSA	%Loaded	#iter	#TN	Imp(%)
C1-1	Yes	No	Day 1	41,503	39,496	56.83	1	70	4.84
C1-2	No	Yes	Day 1	41,503	29,584	52.41	24	132	28.72
C1-3	No	No	Day 1	41,503	25,829	51.90	20	128	37.77
C1-4	Yes	No	Day 2	38,454	36,744	62.03	1	78	4.45
C1-5	No	Yes	Day 2	38,454	27,228	53.17	14	147	29.19
C1-6	No	No	Day 2	38,454	23,518	53.52	13	155	38.84
C1-7	Yes	No	Day 3	33,697	30,432	60.27	1	72	9.69
C1-8	No	Yes	Day 3	33,697	25,880	50.19	16	137	23.20
C1-9	No	No	Day 3	33,697	22,179	53.27	17	143	34.18
C1-10	Yes	Yes	Day 1-3	118,965	116,780	58.60	1	232	1.84
C1-11	Yes	No	Day 1-3	118,965	109,779	61.72	1	230	7.72
C1-12	No	Yes	Day 1-3	118,965	92,584	54.37	3	305	22.18
C1-13	No	No	Day 1-3	118,965	82,210	55.37	2	301	30.90
C1-14	No	No	Day 1	n/a	27,248	51.04	21	133	n/a
C1-15	No	Yes	Day 1	n/a	34,991	50.34	21	132	n/a
C1-16	No	No	Day 1	n/a	30,365	48.02	16	135	n/a

Table 3: Results from Case study 1.

tion cost increases (compared to Case C1-3) but the supply points which have a priority are emptied.

A certain demand point might have a lower demand limit but would like to have more if possible. We simulate this situation by setting priority (bonus) on the demand point and increasing the upper demand limit to 50% more than the lower demand limit. We have done this for the cases C1-15 and C1-16 (where we set a priority on the demand point with the highest demand). Again, the total transportation cost increases (compared to the cases C1-2 and C1-3 respectively) since more logs are transported to the demand point. In these cases, the upper demand limit is reached for the demand point with priority.

Only a small improvement is reached for Case C1-10. This instance is very restricted since the solution has to be very similar to the manual one (since the same vehicles have to visit the same supplies as in the manual solution and exactly the same supply points have to be used).

5.2 Case study 2: Skogsåkarna

Skogsåkarna AB is a haulage firm which is owned by 94 hauliers with together around 110 trucks. The firm (Skogsåkarna AB) uses firstly the trucks owned by the hauliers who are owners of Skogsåkarna AB according to special agreement. When necessary, additional trucks are hired. In their main operating area, Dalecarlia and neighbouring counties, Skogsåkarna haul roundwood for several wood suppliers like Stora Enso, Korsnäs, Mellanskog, and Sveaskog. Stora Enso Wood Supply Sweden is responsible for wood supply to the groupt's Swedish industries and all the wood procurement in Sweden, Denmark, and Norway. They supply about 18 million cubic meters in total annually, most of the wood procured goes to Stora Ensot's mills in southern and mid Sweden. The geographical distribution of nodes for this case study is given in Figure 14.

Figure 14: Geographical distribution of nodes for Case study 2 (demand points: squares, supply points: triangles, home bases: pentagons, changeover nodes: circles).

The purpose of this case study was to analyze the transportation cost over a large region when there are changes in the characteristics. The main parameter to study was opening hours at industries, terminal time for loading and unloading, usage of trucks with/ without crane and differences in transport efficiency for the assortments.

The base case was built based on the actual transportation carried out over five days. The data was collected through Skogsåkarna. In the case we had 110 trucks (78 with a crane and 32 without a crane). The trucks were run in 2.5 shifts and driver change over was done either at special change over nodes or at the home base. The proportion between saw logs and pulp logs was approximately 50/50. More than half of the supply points (1,019) had a volume of less than one truck load.

When solving problems in this section of the paper we used a solution time of 100 minutes. The solution to the base case generated a total driving distance for the trucks of 180,335 km for loaded driving and 182,047 km for empty driving. The total distance from home base to the first loading point each day and from the last unloading point each day to the home base is 57,193 km. The trucks spend 23% (150,990 minutes) of their total working time loading and unloading. The total number of loads delivered by the 110 trucks over five days was 2,705 and the total cost was SEK 5,607,674.

The main results from the case study are based on using a base case and then setting up a number of scenarios where the data is changed. The results are then analyzed to establish some key differences and how large the savings or the cost increases are. The main results can be summarized in the following points.

Opening hours Increasing the opening hours at the industries does not decrease the overall transportation cost significantly. The conclusion is that the opening hours are already quite long.

Crane vs no crane Some harvest areas are using loaders. There are three alternatives for how to empty these. One is to mix trucks with and without cranes all the time without restrictions. A second is to use only trucks without a crane and a third to use trucks with cranes only in the end when there are small (less than a truckload) piles left. The best result is to use the second alternative. The main reason is that the trucks with cranes take away too many potential routes for the trucks without cranes.

Loading time The parameter setting in the base case indicates that 65% of the total loading and unloading time is used for loading. A decrease of 20% in the loading time in the parameter setting with 20% reduces the transport cost by SEK 2 per ton. This represents about 4 % of the overall cost. This has led to further studies to analyze how the loading can be improved.

Driver change over A possibility to use flexible change over nodes shows a relatively large potential (up to 9%) in decreased transportation cost. The change over was allowed to take place at any location with the only restriction that it had to take place within a given time window. No consideration was taken regarding the distance to drive back and forth with a car. However, further studies are planned, since the potential of this is large.

5.3 Case study 3: SCA

With 2.6 million hectares, of which 2.0 million hectares are managed for timber production, SCA is one of Europe's largest private forest owners. SCA's forests are located in the northern part of Sweden and constitute the raw material base for SCA's industries in the region. SCA harvests almost five million cubic meters of timber annually in its own forests. This covers roughly two thirds of the raw material need in the company's Swedish industries. Almost all of the rest of the raw material is procured from local forest owners in the northern part of Sweden. The geographical distribution of nodes for this case study is given in Figure 15. Most industries are located close to the coast.

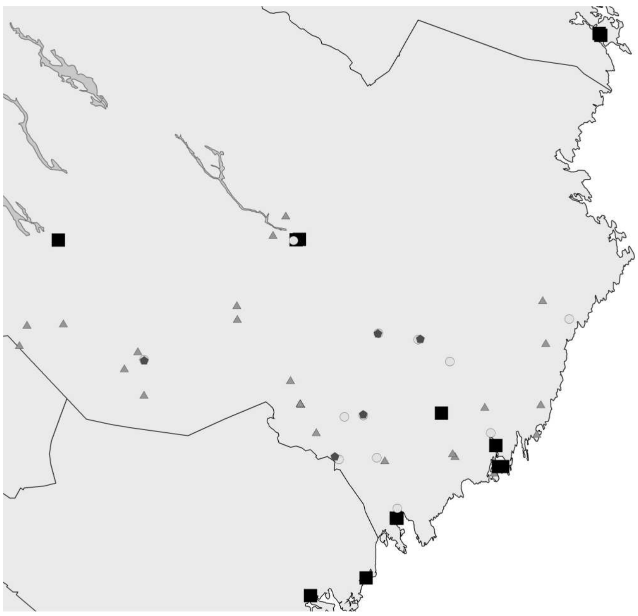

Figure 15: Geographical distribution of nodes for Case study 3 (demand points: squares, supply points: triangles, home bases: pentagons, change-over nodes: circles).

SCA Skog has direct agreements with many hauliers. In the case study, three transporters are involved with 4, 3, and 3 trucks, all together 10 trucks. Each transporter is responsible for all the transports in a certain area. The overall region is characterized by main flows of wood from the inland to the coast. The opportunities for backhauling are limited. The drivers of the trucks kept diaries in order to store information about all the activities over three days. The trucks delivered 109 loads to 8 different industries during these three days. The data for all the 109 loads was put into RuttOpt. Three simulations were made. In the first one (Case 3-1), the trucks of each company were only allowed to load at the sites in their "home area" and the destination was fixed. In the second (Case 3-2), all trucks were allowed to load at any site but the destination was still fixed. In the third (Case 3-3), all trucks were allowed to load at any site and the destination was free. The results were compared with the routes logged in the diaries and are given in Table 4. The distances in the table are taken from RuttOpt to enable a comparison. The case is rather small and the difference in results between manual and RuttOpt will most often not be so big since the planning problem is fairly easy and because of the positioning of demand points the opportunities for backhauling are limited.

Case	Description	Loaded	Unloaded	Total	relative
3-0	Manual	10,844	10,490	21,334	100
3-1	three areas, fix destination	10778	10390	21168	99.2
3-2	one area, fix destination	10,778	9,760	20,538	96.3
3-3	one area, free destination	10,614	9,557	20,171	94.5

Table 4: Distances (loaded and unloaded) expressed in km driven in Case study 3.

5.4 Case study 4: VSV

VSV is a transportation and logging company and is one of the major operators in forestry industry logistics in their part of the country. VSV offers a number of specific services to both public and private forest companies, as well as to forest administrators. The main services are logging and transportation of round timber, wood-chips, and bio-fuels. VSV's fleet of vehicles includes among others, 180 log trucks. The geographical distribution of nodes for this case study is given in Figure 16. Here, the industries are spread and there are many potential backhauling alternatives.

In this case, eight transporters are involved with a total of 10 trucks. Each transporter is responsible for all the transports in a certain area. With the help of data from SDC, the routes of the ten trucks for three days were simulated. The trucks delivered 120 loads during the three days to 19 different industries. All the corresponding data were put into RuttOpt. The result given in Table 5 shows a potential saving of 20.2% of the driven distance. With better combinations of loads and trucks the potential for savings is substantial when working with the entire fleet of trucks instead of each transporter individually.

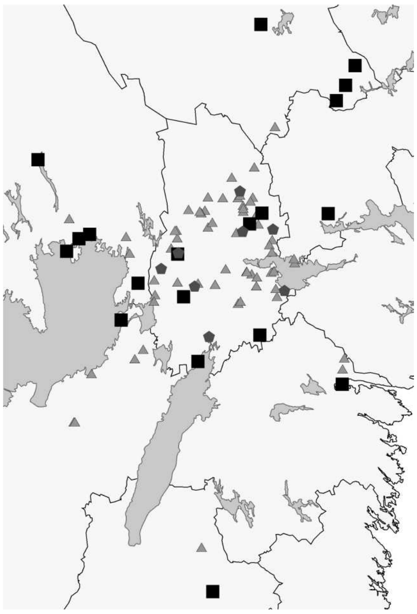

Figure 16: Geographical distribution of nodes for Case study 4 (demand points: squares, supply points: triangles, home bases: pentagons, change-over nodes: circles).

Case	Description	Loaded	Unloaded	Total	relative
4-0	Manual	9,542	8,778	18,320	100
4-1	eight areas, fix destination	9,520	6,679	16,199	88.4
4-2	one area, fix destination	9,508	5,504	15,012	81.9
4-3	one area, free destination	9,130	5,481	14,611	79.8

Table 5: Distances (loaded and unloaded) expressed in km driven in Case study 4.

6 Concluding remarks

We have described the transport planning situation in Sweden and the new DSS RuttOpt in detail. All the components for daily routing in a practical setting are included and are integrated through one user interface. An important part of the system is the access to a digital, nation-wide road information system through the road database NVDB. A second part is a robust and efficient route planner. The system has been developed in order to be usable by both forest companies and transporters depending on the organisation of the transportation used. The case studies show that the routing component works for large scale problems and that the quality of the solutions is high.

One of the case studies shows that RuttOpt can be used to make simulations where characteristics are changed in order to identify bottle necks and operations with high potential to reduce the transportation cost. The case studies also show that integrating several smaller areas may decrease the overall cost substantially. The case studies have initialized further projects, including ways to reduce loading time and allocate costs fairly among participants.

The RuttOpt system was tested on-line during the period of one day for VSV (Case study 4). A full schedule was created and this information was given to the drivers. However, it turned out that the road side inventory was wrong. For example, according to the system, there was a full truck load available at a location but when the truck arrived, the forwarding operations had not started. Another example was that a road that RuttOpt was using was closed that day because of snow removal. It is very important that the data about supply and roads is correct. SDC can be used to update the supply, but it is important that the supply information is accurately updated. The updating needs to be done jointly by the trucks and forwarders so it is clear how much has been put in the piles by the forwarders and how many truck loads have been removed. The road information also needs to be updated on a daily basis. An alternative is that the planner easily can insert local information about closed roads.

In order to create effective routes for trucks there is a need for the exchange of transport orders between companies, hauliers, and trucks. This will require a standardized means to communicate. Digital standards for transport orders and load specification will probably be introduced in Sweden during 2007. Efforts are being made to establish an international standard for wood supply as a part of papiNet which is a global community involved in supply chain processes for the forest and paper industry. There is also a need to have an IT system in each truck in order to provide information about routes and information updates. Today, most of the trucks do have such systems.

Using systems like RuttOpt is to move towards a central planning. The overall system will perform better but single trucks may get worse routes. It is therefore important that the overall cost is allocated correctly among participants so that all are motivated. Today, there is a rebate split between the transporter and the forest company when using backhauling routes. A new rebate based on fleet performance can be used to cover trucks with less good routes. There are several options for how to allocate costs and/ or savings based on economic models. Such models are being studied in an ongoing Skogforsk project together with four forest companies. It is also important that all participants accept the cost sharing principles and are motivated to take jobs that are considered less profitable. One example is to visit several supply points with volumes less than a truckload. In such cases, the time to load a truck at multiple supply points for one full load is considerably longer than loading a full truck load at one supply point. A way to motivate the former is to assign a bonus for each small supply point emptied. To establish a basis for such cost allocation system is a future research topic.

The unloading operation in itself is regarded as efficient but there is a large potential associated to avoid queuing for volume measurement and unloading at the demand points. In most routing systems, including RuttOpt, queuing is not included and hence more than one truck may arrive at a demand point at the same time for volume measurement and unloading. This is an important part of a DSS for routing to be accepted in practice. This feature is one development of RuttOpt in the future.

References

[1] Cordeau J.-F., Gendreau M., Laporte G., Potvin J.-Y., and Semet F. 2002. A guide to vehicle routing heuristics. Journal of the Operational Research Society. **53**: 512-522.

[2] Cordeau J.-F., Laporte G., and Mercier A. 2001. A unified tabu search heuristic for vehicle routing problems with time windows. Journal of the Operational Research Society. **52**: 928-936.

[3] Ekstrand M., and Skutin S.-G. 2005. Processkartläggning av transportledning och transporter. Arbetsrapport Skogforsk, No. 596. (In Swedish)

[4] Epstein R., Morales R., Seron J., Traverso P., and Weintraub A. 1996. A truck scheduling system improves efficiency in the forest industries, Interfaces. **26**(4): 1-12.

[5] Eriksson J., and Rönnqvist M. 2003. Decision support system/tools: Transportation and route planning: Åkarweb - a web based planning system. Proceedings of the 2nd Forest Engineering Conference, Växjö, May 12-15, Sweden, 48-57.

[6] Flisberg P., Liden B., and Rönnqvist M. 2007. A hybrid method based on linear programming and tabu search for routing of logging trucks, Scandinavian Working Papers in Economics, NHH Discussion Paper 14/2007.

[7] Forsberg M., Frisk M., and Rönnqvist M. 2005. FlowOpt - a decision support tool for strategic and tactical transportation planning in forestry, International Journal of Forest Engineering. **16**: 101-114.

[8] Forslund M. 2007. Skogsåkarna AB, private communication, April.

[9] Gendreau M., Laporte G., and Potvin J.-Y. 2002. Metaheuristics for the Capacitated VRP. In: Toth P, Vigo D, editors. The Vehicle Routing Problem. SIAM Monographs on Discrete Mathematics and Applications, SIAM, Philadelphia, PA. 129-154.

[10] Gingras C., Cordeau J.-F., and Laporte G. 2006. Un algorithme de minimisation du transport à vide appliqué a l'industrie forestière, Report CIRRELT, Montreal, Canada.

[11] Gronalt M., and Hirsch P. 2005. A tabu search based solution method to optimize round timber transport. Proceedings of the MIC2005: The sixth Metaheuristic International Conference, Vienna, Austria, August 22-26.

[12] Johansson L. 2007. Holmen Skog AB, private communication, April.

[13] Kallin J. 2007. Sydved AB, private communication, April.

[14] Murphy G. 2003. Reducing trucks on the road through optimal route scheduling and shared log transport service. Southern Journal of Applied Forestry 2003. **27**(3): 198-205.

[15] Palmgren M. 2005. Optimal truck scheduling - mathematical modeling and solution by the column generation principle. PhD Thesis, Dissertation No. 967, Linköping University.

[16] Palmgren M., Rönnqvist M., and Värbrand P. 2003. A solution approach for log truck scheduling based on composite pricing and branch and bound. International Transactions of Operations Research. **10**(3): 433-448.

[17] Palmgren M., Rönnqvist M., and Värbrand P. 2004. A near-exact method for solving the log-truck scheduling problem. International Transactions of Operations Research. **11**(4): 447-464.

[18] Parklund T. 2007. VSV, private communication, April.

[19] Rönnqvist M. 2003. Optimization in forestry. Mathematical Programming Ser. B. **97**: 267-284.

[20] Rönnqvist M., and Ryan D. 1995. Solving Truck Despatch Problem in Real Time. Proceedings of the 31th Annual Conference of the Operational Research Society of New Zealand, August 31-September 1, Wellington, New Zealand, 165-172.

[21] Rönnqvist M., Sahlin H., and Carlsson D. 1998. Operative planning and dispatching of forestry transportation, Report LiTH-MAT-R-1998-18, Linköping University, Sweden.