Optimisation of Forest Road Investments and the Roundwood Supply Chain

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Abstract

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In a pre-study, concerning roundwood freshness, performed by the Forestry Research Institute of Sweden during the spring of 2000, the quality on the forest road network was identified as a major problem for the Swedish forest sector. These problems mostly occur during spring thaw, but also when rains give muddy gravel roads. The Swedish forest company Holmen Skog decided to support the PhD project presented here with harvest and road data from a forest district, and expert knowledge of road investments. Upgrading of forest roads has been studied in a major part of this thesis, with two case studies at a forest district of average size located around Sveg in Härjedalen. Deterministic scenario analysis has been used and compared to a two-stage stochastic model. Cost functions, assortment mixtures and scenarios have been analysed, and results have been evaluated together with the staff at Holmen Skog. These case studies indicate that the problem can swiftly be solved, at least at average size forest districts.

In the last paper a model of the roundwood supply chain is developed and tested via a sample problem. The problem is restricted to the supply chain with fixed harvesting and fixed demand at the mills. The considered uncertainty is load-bearing capacity on the road network, which depends on the water content in the road body and the bearing layer quality. In contrast to the road investment which are long-term decisions, this planning problem is short-term, and in our paper between half a year and one year. One difficult part in this model is the estimation of storage costs. This study, therefore, puts forward the need of measurements of storage costs. Otherwise, it is not possible to optimise the roundwood supply chain in a consistent way. Storage costs should, for that reason, be analysed in the future.

Keywords: Stochastic Programming, Scenario Analysis, Mixed-Integer Linear Programming, Forest Logistics, Upgrading of gravel roads.

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Contributions to co-authored papers

Two of the papers (paper I and paper V) were prepared in co-operation with my supervisor Peter Lohmander. The other papers (II,III,IV) were prepared purely by myself. Paper (I,II,III,IV) used data from Holmen Skog. The conclusions in papers (I,II,III) was supported by disseminations during meetings with the staff at Holmen Skog.

I. Optimal forest transportations with respect to road investments

Ideas and the model structure were discussed and the text was developed together with Peter Lohmander. I developed the model, performed implementations using the LINGO software and analysed the results.

V. Adaptive optimisation in the roundwood supply chain

The work in this paper is an extension of ideas presented by Peter Lohmander in the Symposium on Systems Analysis in Forest Resources in Chile 2001. Therefore, Peter is the first author on this paper. This model has been extended in co-operation between the authors. I did the implementation with the LINGO software of the extended model and analysed the results. Peter wrote the introduction. Both authors, together, wrote the abstract, the problem description, the discussion, the conclusions and the reference list.

Contents

Introduction

Background

Assume that you are the owner of a large integrated forest company with many different forest stands covering large geographical areas. The harvester and forwarder capacities are limited, and there is a constraint on the number of trucks. A number of geographically distributed sawmills and pulp-mills must be supplied regularly – in order not to stop the processes or close them down. There are set-up costs in production. There are economies of scale in harvesting operations. There are environmental regulations in the forest act, constraining the company's activities. Of course, one could argue that every part of the company should buy and sell goods on the markets. Then, however, if one ignores the coordination aspects, the available fleet of harvesters, forwarders and trucks cannot be used in the most profitable way. Harvesting decisions in different areas and time periods, storage[1] at different sites, and industrial production and investment decisions also have to be treated in a logically consistent manner. It is obvious that operation research methods are needed which can handle such problems. We can no longer assume that the decisions in harvesting, transport and forest industry are independent.

Forest sector logistics is the field that connects decisions from harvesting operations to the forest industry. A large number of applications of methods from operations research and management science are to be found in this area. This has been reported by, for example, Martell et al.(1998), Carlsson et al.(1998), Carlsson & Rönnqvist (1998), Rönnqvist et al.(1998) and Karlsson (2002). The field is rapidly expanding, but is still rather new. Consequently, there are many problems that have not yet been properly investigated.

Transportation science and logistics are other research fields in which operation research techniques have been used extensively. Many model types, for example, Vehicle Routing Problems (VRP) (with a good survey of heuristic methods in Cordeau et al. (2002)), and network design models (Cordeau et al. 2003; Crainic 1998) are also applicable to forest logistics. Examples of VRP models in forestry can be found in Palmgren (2002) and Palmgren et al.(2002). Network design models are used in this thesis but have also been used by Karlsson et al. (2002), for example, to model road investments. Nevertheless, in forestry, we have to deal with raw material that cannot in general be stored without loss in quality. This is a major problem for the forest sector, and many studies relating to the storage of roundwood have been reported during the years. One study dealing with Spruce pulpwood was published by Persson & Elowsson (2001). Most of these studies, however, have not focused on the quantitative measurements of roundwood storage that are required for storage cost estimations.

[1] Note that with storage, in this thesis, we mean the roundwood stored on the ground and not the growing stands in the forest.

Another problem in forestry is that most of the activities are highly integrated, and should be planned jointly. Many examples of integrated planning using optimisation can be found, e.g. for Swedish conditions in Karlsson (2002), Bredström et al. (2001) etc. Furthermore, there are many geographical and weather-related differences which make forest management in general a very challenging task. For instance, in Sweden spring thaw gives major transportation problems, since the load-bearing capacity, especially on gravel roads, becomes very limited during these periods (Hossein, 1999; Löfroth et al., 1992). Note that this problem does not even exist in many other parts of the world.

In recent years, there has been increased interest in the use of pulpwood for bio-energy purposes. This may be a threat to the pulp industry, since it can sometimes be more profitable for the forest owner to sell potential pulpwood as bio-energy, as put forward by Johansson (2001), especially as there is often a shorter hauling distance to the bio-fuel plant than to the pulp-mill. This is due to the fact that there are few large pulp-mills but many small bio-fuel plants in Sweden.

Studies using operations research methods to manage the bio-energy supply chain can, for example, be found in Gunnarsson et al. (2001). However, the use of wood as bio-fuel is not considered in this thesis. This thesis consists of two parts:

1. Forest road investments
2. The roundwood supply chain

The major part of the thesis is devoted to forest road investments (four papers), and in particular the upgrading of forest road networks. Modeling of the roundwood supply chain is a rather different issue to that of road investments, since forest road investments are long-term decisions (in our case, ten years) but the roundwood supply chain model involves short-term decisions. This is the major reason behind dividing the presentation of the two subjects into distinct parts in this thesis.

Forest road investments

Background

Road quality is very important to Swedish forestry, since almost all domestic roundwood is hauled some distance on roads by trucks. Road quality has been identified as being a major problem by the Swedish forest sector. A better strategy for road investments than that presently used will probably generate major savings for the forest sector in the future. Problems involving roads occur during the spring thaw and when rains give muddy gravel roads, mostly during the fall (Figure 1). High water content destroys the gravel layer on the roads during these periods. This is described by Hossein (1999).

Fig. 1. A typical gravel road during a critical period in Sweden.

Different types of road investment decisions occur in forest companies. However, we concentrate here on the long-term planning of upgrading of gravel roads. This is an important forest logistics problem in Sweden. In order to secure the roundwood demand at the mills under the thawing period in the spring, Swedish forest companies must decide either to have a large security stock of roundwood, or to invest in gravel roads. There is probably some combination of security stock and road investments which is optimal during the spring thaw, as depicted in Figure 2. Note, however, that the costs in Figure 2 are only examples, and that in general, storage costs in particular are very difficult to estimate.

This planning problem is also difficult when rains damage the roads, mainly during the fall. In contrast to the thawing period which is known to come in the spring, we never know if, when, or how much it will rain during a year.

The staffs of the forest company Holmen Skog is convinced that the only way of transporting internal roundwood to the mills during periods of rain is to invest in higher road quality. The reason, they claim, is that we cannot build up the security stock to compensate for rainy periods, since rain is too unpredictable. Moreover, we cannot store most of the roundwood assortments, especially spruce pulpwood (Persson et al., 2002), for any length of time during the summer and fall without major loss of quality. These quality losses are very hard to predict and depend on many factors such as weather, geographical location and type of assortment.

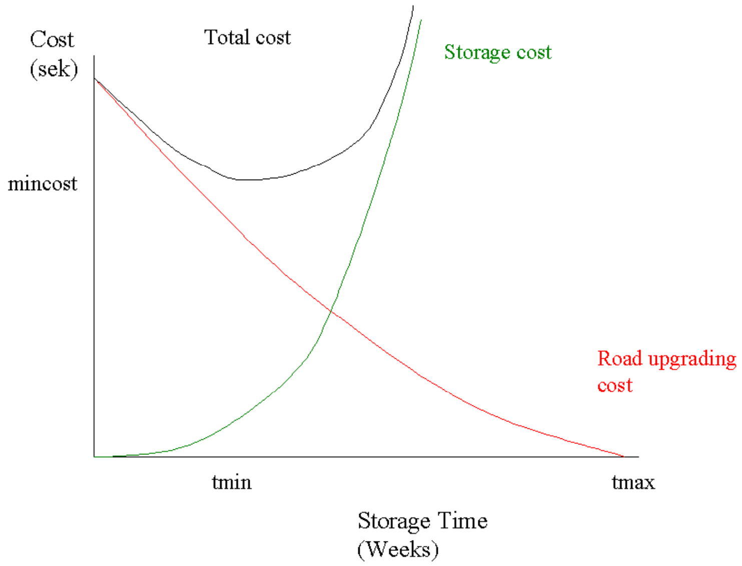

Fig. 2. The minimal total cost (*mincost*) with respect to both road upgrading and storage cost is obtained if we store the roundwood for *tmin* weeks during the spring thaw. The length of the spring thaw is assumed to be *tmax* weeks in this picture. Note that the costs in the picture are only examples of how the costs might look. Note also that storage is usually not an option during rainy periods, since the amount of rain is not known at the time of planning.

In recent years, the interest at Holmen Skog has been moved from harvest decisions, which have been relatively well investigated, to forest logistics – and especially how to upgrade gravel roads. The company is in need of support concerning long-term decisions on how to improve roads. Furthermore, contracts concerning road improvements are very important since many of the forest roads are owned jointly by the forest company and by individuals who own small pieces of land. The private forest owners often have no interest in road investments, since they do not personally use the roads for heavy trucks and loads. Hence, the company needs to know well in advance what roads to invest in over a longer period in order to justify road improvements to all parties involved.

In a preliminary study concerning roundwood freshness at Holmen Skog's Iggesund region during the spring of 2000, road quality was identified as being the major problem for them (Skutin & Arvidsson, 2000). The problems mostly occur during the spring thaw, but also when rain leads to muddy gravel roads. The problem for Swedish conditions had not been studied with operation research methods before, although since the start of the project presented here, some studies have been published, e.g. Arvidsson et al. (2000), Karlsson et al. (2002)

and Karlsson (2002). Thus, in 2000, Holmen Skog decided to support the Ph.D. project presented here.

Road transportation is dependent on the structure of the road network. Hence, network flow models (Rardin, 1998) should be used to avoid sub-optimal solutions. The road upgrade problem considered can be viewed as a larger instance of the sample network design model depicted in Figure 3.

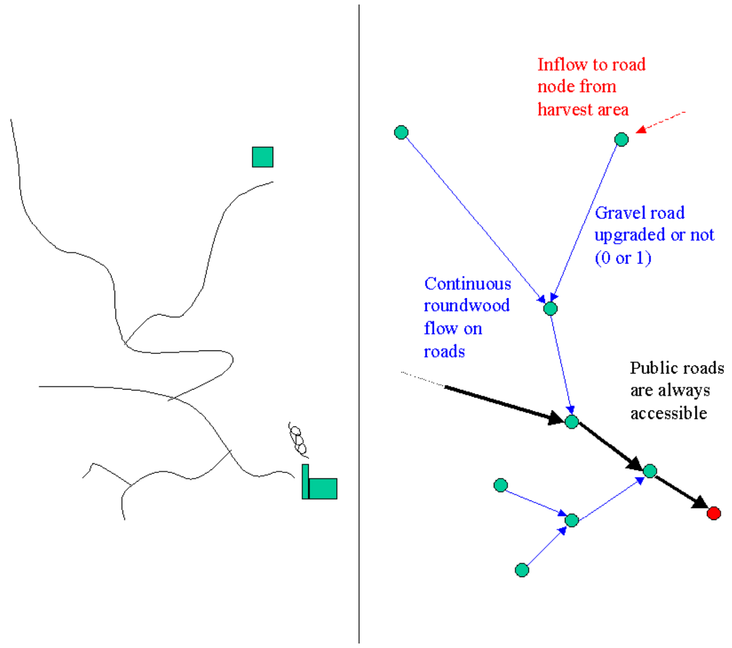

Fig. 3. The real-world sample problem is depicted on the left-hand side, and the network design model used in the road investment optimisation is shown as a network on the right. Note that road upgrade decisions are binary and flow variable continuous. The linear optimisation model is thus mixed-integer.

Network flow problems have been under study for a long time (Weintraub, 1974). Linear programming (LP) approaches have been used, since it has been interesting and highly relevant to explicitly consider and handle the links between decisions in forest harvesting, logistics and forest mills, as discussed by Weintraub (1976) and Barros & Weintraub (1982).

However, in the case described in Figure 3, mixed-integer linear models represent the problem in a better way than continuous variable models do, since there are both variable and fixed costs involved when we upgrade gravel roads. We have to decide whether we want to upgrade the road or not, and this clearly provides a binary variable for each road. However, the roundwood flow variables are continuous.

Furthermore, the network formulation of the road upgrade problem depicted in Figure 3 is unbalanced with supply surplus, meaning that there is more roundwood available at road-side storage than the industry requires. This problem can be solved in many different ways. In the papers presented here, we have chosen to balance the networks by the introduction of a virtual supply node. This dramatically shortens the calculation time on our cases, due to the fact that the LP-relaxation bound becomes stronger (Wolsey, 1998). The idea is that the ordinary supply nodes are transformed to transhipment nodes, and a constraint is added to the link between the virtual supply node and the old supply node (Figure 4.). This constraint is the upper bound of the supply at this node. Furthermore, the supply at the virtual demand is set to equal the total demand. Since we only have one demand node in our case study, this will give us a network formulation with only one supply and one demand node.

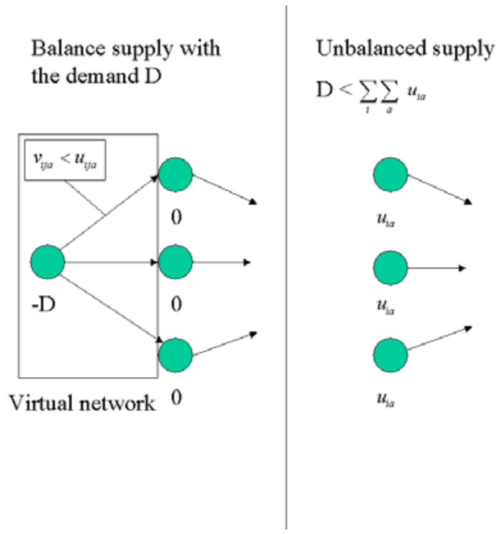

Fig. 4. The difference between a balanced network with a virtual supply node and the original unbalanced network is described above.

An example of a formulation of a mixed-linear model in two dimensions is described below.

$$\min \sum_{(i,j)} c_{ij} v_{ij} + \sum_{(i,j)} f_{ij}\ x_{ij}$$

$$s.t$$

$$v_{ij} < Mx_{ij}$$

$$\sum_i v_{ij} - \sum_i v_{ji} = b_j$$

$$etc.$$

The key point is that we jointly minimize the cost of a part with continuous variables (v_{ij}) and a part that has binary variables (x_{ij}). These variables are also connected in the model through at least one constraint. An example of such a constraint is the first constraint in the model above. We also have a conservation of flow constraint in a network model where $b_j= 0$ if it is an transhipment node, $b_j>0$ if it is a demand node, and $b_j< 0$ if it is a supply node. This is the second constraint described above. The cost function is minimized with respect to at least these constraints, but naturally, in most cases other constraints also are added to the model.

Including binary variables in LP models usually gives us a much harder optimization problem, since we usually come up with a non-convex constraint set. To solve this mixed-linear problem to global optimality we have to use cutting plane methods together with branch and bound, combined with ordinary solution methods for LP problems, such as the simplex algorithm. These methods are called branch and cut (Wolsey, 1998).

In the past, due to the non-convexity problem, mixed-integer linear formulations of forest planning models have usually been solved with different heuristic or meta-heuristic methods (Aarts, 1998) as described in, for example, Weintraub et al. (1994, 1995). Some Swedish forest logistics projects using heuristics can be found in Karlsson (2002), Bredström et al. (2001) and Carlsson & Rönnqvist (1998). Today, however, with increased computer speed and better optimization software, it is possible, at least in our case, to solve all the models considered in this thesis to global optimality, or near-optimality, using commercial software with branch and cut algorithms. If we want to stop early in the solution process, branch and cut algorithms always give us a worst case bound from true optimality, despite many heuristics.

Algorithms that combine branch and cut algorithms with constraint programming (Lustig & Puget, 2001; Marriot & Stuckley, 1998) can probably shorten the solution time considerably in the future, since the network formulations used for the road investment problem have a weak LP relaxation. However, these methods are not used here.

The case studies

Two case studies were performed together with Holmen Skog at an area located around Sveg in Härjedalen. This area is located in the middle of Sweden. This case study area, depicted in Figure 5, can be considered to be a forest district of normal size in Sweden. The Iggesund region consists of this district and four other districts of similar size.

A representative road investment problem for the Iggesund region at Holmen Skog thus includes about five times the number of roads featured in the two case studies in Sveg, which are presented in papers II, III, and IV. Hence, with our models, it will be possible to solve a regional-sized problem to near-optimality with some proper heuristic methods in the future, at least with the deterministic models presented in papers II and III.

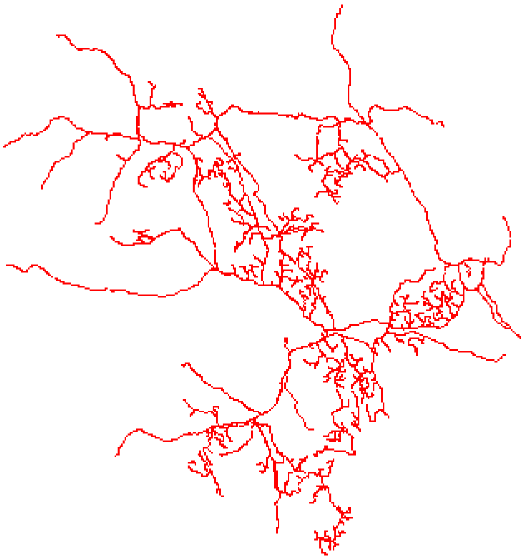

Fig. 5. The forest road network used in the case studies is located in the middle of Sweden. It consists of 440 roads.

In all of the papers, we use the standard forest sector road classification described by Löfroth et al. (2000):

- Roads accessible the whole year are considered to be class A.
- Roads accessible the whole year, except thawing in the spring, are class B.
- Roads only accessible during summer and winter seasons are class C.
- Roads accessible only in winter, when the ground is frozen, are class D.

Most of the gravel roads in the case study area (Figure 5) used in papers I, II, III and IV are of class C. It is common practice to build gravel roads of this class in the Sveg area. Moreover, there are no gravel roads of class A in that area.

The following data were provided by Holmen Skog:

- Harvest volumes from their 10-year harvest plan linked to roadside storage at 320 nodes in the network in Figure 5. In papers I and II, only total volume were used. In papers III and IV, the volumes were divided into three different assortments. However, since there is almost no hardwood available in this area, only Pine and Spuce assortments were considered in these studies.

- Road data, such as length, width, initial gravel thickness and distance to the nearest gravel pit etc.
- Road upgrading and transportation costs.
- Definition of the network structure in ArcView.

Since there is no general road upgrade function available at present, the staff at Holmen Skog estimated the road upgrade function in paper II. In fact, there has been almost no research about gravel roads since World War II (Hossein, 1999). This estimated road upgrade cost function, given below, consists of fixed costs a, length dependent costs b and gravel volume dependent costs c. These costs could also be specified for every single road in the network if one were to add indices to these parameters. However, this is not done in our study. A more detailed description of the cost function stated below is given in paper II.

$$f(\Delta h_{ij}, l_{ij}) = a + (b + c\Delta h_{ij})l_{ij}$$

The functional form of this cost function can be discussed. It does not take economic scale factors into account. In the real world, the fixed cost would be lower if several objects connected to each other were upgraded at the same time. Another problem is that it is very hard to know in advance where to pick up the gravel. The assumption in paper II that it is always possible to open up new gravel pits is definitely not true in general. This cost function is, therefore, rather specific for the case study area. It is also possible to use different types of gravel in the body of the road, but in Sveg sandy moraine was used everywhere.

Aims of the studies

Paper I describes a dynamic network design model for road improvements. However, in the other road investment papers we chose to concentrate purely on spatial aspects of the road network (Figure 3), since we wanted to use the models developed for large road networks in the future.

From the viewpoint of a forest economist, skipping the dynamic aspects seems strange – since the growth of the standing volume that affects the optimal rotation age is usually an essential part of forest economics (Johansson & Löfgren, 1985). Furthermore, the time value of money is not considered. However, in these papers, static models are chosen since more detailed deterministic models will probably not approximate the real world problem in a consistent manner, due to the stochastic behaviour of the weather. A relevant dynamic multi-stage stochastic model would unfortunately not be solvable in reasonable time, even for sample problems, at present.

On the other hand, the results delivered from these static optimization models could be viewed as the optimal solutions if we did all the investments today. This is a big step forward for Swedish forest companies compared to the situation today, where no decision aids exist at all.

Papers II and III of this thesis are focused on the case studies applied to forest roads owned purely or partly by Holmen Skog (Figure 5). In paper IV, a two-stage stochastic model (Birge & Louveaux, 1997; Kall & Wallace, 1994) is compared to the deterministic model developed in paper III, since deterministic scenario analysis can have substantial drawbacks when applied to real-world problems. Excellent examples describing these deficiencies with scenario analysis are described in Wallace (2000, 2003).

In paper III, we compare the cost of upgrading to the costs of other alternatives. There are problems also with surfaced roads and other public roads. These problems have been studied by Arvidsson & Holmgren (1999a, 1999b) and Arvidsson & Jönsson (2000), for example. However, in our case studies, the forest company is not allowed to upgrade such roads. Thus, these studies focus purely on upgrade of gravel roads.

To our knowledge, our models presented in the four papers and the models published by Arvidsson et al. (2002), Karlsson (2002) and Karlsson et al. (2002) are the only optimization models available for upgrading of roads under Swedish conditions, though only the model in paper IV considers uncertainty aspects. This model is two-stage stochastic (Birge & Louveaux, 1997), where we assume that we do not know the critical period length, such as the length of the spring thaw and rainy periods in advance.

The philosophy behind modelling uncertainty with stochastic programming is that solutions should give the decision maker options when disturbances occur, in real life. Another common way to view uncertainty in economics is option theory, and especially real options (Amram & Kulatilaka, 1999; Wallace, 2003). Note that a real option is an extension of the financial option concept described by Kolb (1995) and Brandrup-Wognsen & Stenbom (1986) to options on real assets. Stochastic programming and real option theory is, therefore, different ways to handle the same uncertainty.

The stochastic model in paper IV (Figure 6.) is the decision problem when we include uncertainty in the model, and is described in some detail below.

- The decision-maker wants suggestions from the decision support system concerning which of the roads are optimal to upgrade during a long-term period (in our case, ten-years).
- Road investment decisions are made together with other forest owners, and contracts are signed in co-operation with all other parties. This is the first-stage decision, taken before knowing the actual length of the average critical period (Figure 6.).
- The average critical period length is observed (Figure 6.). Note that the whole 10-year period is handled as one period. Hence, it is the average length during this period that is considered. With the three-week scenario, we thus consider an average of three weeks of bad roads every year, during the ten-year period. Thus, at this planning level, it is understood that we do not consider the individual changes during every year.

- Transportation decisions have to be made after the observation of the average critical period length. This is the second-stage decision (Figure 6). This could be viewed as the transportation policy being dependent on what scenario would happen in the future. Unfortunately, this cannot be known at the time we make road improvement decisions.

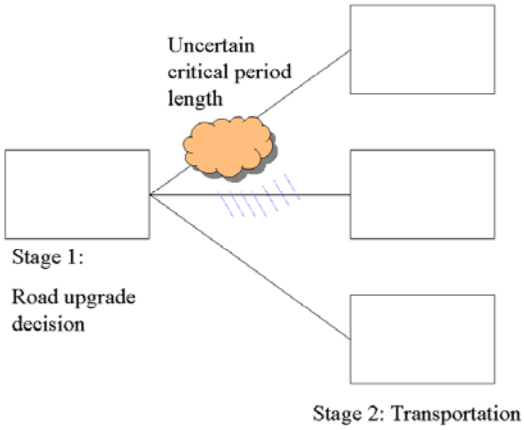

Fig.6. The two-stage stochastic model with three critical period length scenarios. The decisions about upgrading of roads are taken before knowing the actual future state of the critical period length, and transportation on the road network is performed afterwards.

Of course, corrections to the road investment plan have to be made after observation of the critical period length. This is, however, not a part of the long-term planning considered in our models. On the other hand, in contrast to the deterministic model, the stochastic model will already take some uncertainty into account. The roads suggested from the calculation output are, thus, optimal with respect to the uncertainty aspects considered in the stochastic model. In spite of this, deterministic model solutions will have no options left, when disturbances occur in real life, since these models assume perfect knowledge about the future. Nonetheless, as shown in paper IV, there are no substantial differences between the solutions from these two approaches, and in our case, solutions from the deterministic model approximate the true stochastic solution rather well. Note that this need not be true in general!

We conclude that in our case, the deterministic model can be used together with scenario analysis to approximate the true stochastic solution "near optimally" in an efficient and accurate manner. Furthermore, the two-stage stochastic model presented in paper IV evaluates the deterministic model efficiently, at least on problems of an average forest district size with the roundwood flow split into different assortments.

Note that in general, when using the stochastic model for evaluation of the deterministic model output, its only has to be calculated when some parameters change in the model. Thus, with this approach, large problems that take a long time to solve with the stochastic model could be solved once to analyse the value of flexibility. However, when solving the model several times – as required to receive the total, marginal and average cost of upgrading – as described in paper III, the deterministic model is used through scenario analysis to approximate the stochastic model output.

The Roundwood supply chain

Uncertainty, economics and coordination in the supply chain

Typical decision-making problems for companies in the forest sector and in several other sectors of the economy are sequential. A series of decisions is made over time. Important information that was not available (or perfectly predictable) when the first decisions in the chain(s) were made becomes available before the final decisions have to be made. In this situation, the optimal first (and later) decisions in the chain cannot usually be found via the deterministic multi-period optimization methods that are described in, for instance, Winston (1994) or Rardin (1998).

Stochastic dynamic programming can handle decision-making problems of this type. Dynamic programming was invented by Bellman (1957). Winston (1994) and Rardin (1998) have given good descriptions of this approach and related methods of numerical optimization. Usually, however, stochastic dynamic programming cannot be used efficiently when the state space has many dimensions and high resolution in the state and control spaces is needed. Birge & Louveaux (1997) and Kall & Wallace (1994) are good references on other optimization methods for stochastic problems and give applications to different fields.

Problems in forestry can be expanded in many different directions. We may consider large numbers of connected decision-making problems. Several of the forestry problems associated with risk and uncertainty together with optimization procedures are described in Lohmander (2000, 2001). Lohmander (2002) contains a discussion of the ideas in forest economics put forward by Faustmann (1849), and their relationship to later discoveries in the field, based on stochastic dynamic optimization.

The study by Lohmander (1989) was one of the first to deal with adaptive forest logistics under the influence of stochastic markets. A major problem for an artificial forest company with several forest industry mills is defined as a finite time stochastic dynamic programming problem. For each possible state and stage, subordinate problems are solved via linear programming. A stochastic infinite time production and stock level optimization problem for an artificial forest company can be found in Lohmander (1992).

In Lohmander (1993), an optimization model is developed that can determine the optimal production capacity and, simultaneously, the stochastic decision rules to be used in the input and output markets. The approach was based on simulation of all activities in the firm and "quasi-gradient" optimization of the decision rules. The stock levels were also optimized indirectly. The numerical results were compared to the corresponding results from a less detailed analytical model. Both models led to the conclusion that the optimal production capacity is higher in the presence of price risk than in a deterministic market. The "quasi-gradient" method has been well described by Nash & Sofer (1996).

One way of handling rapidly changing conditions is to decentralize decisions to local decision-makers. Local decision-makers can sometimes change their plans more swiftly if they are responsible for their own actions. It may take considerable time to create and communicate a new detailed plan for all units in a large firm. Taxi companies are examples of this. Usually, customers appear randomly and the individual cab driver has to react instantly.

Lohmander (1994) and Lohmander (1997) presented versions of these ideas that were applicable to forest companies. Forest farmers randomly delivered timber and pulpwood at different locations. Adaptive decision rules were optimized for individual truck drivers. The objective was to obtain the best possible economic result at the forest company level. The truck drivers should react as promptly as possible and act correctly according to the decision rules.

The classical multi-period logistics optimization models, first introduced to forest problems by Weintraub (1974), are based on linear programming. Modern versions of these models include integer and mixed-integer formulations. Many road building (Karlsson, 2002), truck scheduling (Palmgren, 2002) and supply chain problems (Bredström et al., 2001) of this type have been described and analyzed with impressive results in recent years. In several cases, however, it is obvious that the model parameters of future planning periods, snow etc., affect the quality of forest roads.

Clearly, we cannot expect a detailed multi-period plan for all trucks and transport to be optimal or feasible in cases where we do not know the road conditions in the later periods. However, we may have statistical information concerning the frequency distribution of rains and similar problems. We may also determine functions describing the relationship between road quality and rain conditions. Remember, however, that it is not possible to predict many of these events at all (Prigogine & Stengers, 1984).

In principle, stochastic dynamic programming could handle this problem with sequential rain information. But, as we know, the number of state dimensions in most forest logistics problems is much too high for stochastic dynamic programming. Hence, we require another adaptive method.

Lohmander (1994b) presented such an adaptive multi-period linear programming approach, connected to the corresponding stochastic dynamic programming method, to the same decision-making problem from resource economics. In that paper, the decision problem did not come from logistics. However, the adaptive multi-period structure was the same. In that particular problem, since the number of state dimensions was low, stochastic dynamic programming turned out to be a computationally superior approach. The results obtained were, however, identical when the number of periods was sufficiently low. The alternative method is sometimes referred to as stochastic scenario optimization or adaptive optimization. Birge & Louveaux (1997) have described and reported different applications of this approach. It is very important, however, not to get the impression that one complete set of optimal decisions is calculated for each possible scenario, since this scenario analysis approach is not optimal in general, as described in Wallace (2000, 2003).

On the contrary, all possible future developments should be considered at each time point in the decision-making problem, building an event tree. An example of such an event tree is depicted in Figure 7.

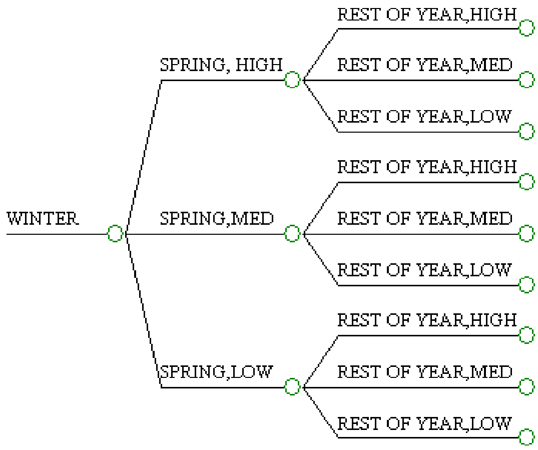

Fig. 7. The event tree for three time periods and three different load-bearing scenarios. Note that the information in this tree structure is connected so that future decisions depend on the actual state of past decisions. Hence, the output from this adaptive optimization gives results similar to those of stochastic dynamic programming (SDP), whenever SDP can be used.

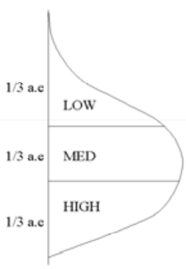

Fig. 8. The probability density functions could be divided so that one-third of area units (a.e) are assigned low water content, one-third medium water content and one-third high water content. Thus, it is always possible to achieve a uniform distribution.

The adaptive optimization approach using the event tree in Figure 7, to connect the scenarios in an appropriate way, is the method we have used in this study. How many scenarios should be used, and what probability distribution to use, is of course not obvious. However, when using adaptive optimization, the important part is to include uncertainty, and of course we should use as many scenarios as possible with respect to the problem and the calculation time. Concerning probabilities, we have used a uniform distribution in paper V, since it is always possible to divide the probability density function in a way that gives us a uniform distribution – as depicted in Figure 8. Furthermore, it is possible to assign arbitrary properties to the transition probabilities (Blom, 1984).

One might argue that probabilities only measures if an event occurs or not, and thus not the degree of which an event occurs. This fuzziness described by, for instance, Kosko (1992) is a relevant future extension of the model. However, it is not considered here.

Aim of the study

The scenarios concerning high, medium or low water content of the roads during different parts of the year are presented in Figure 7. This also gives different load-bearing capacities to the roads. This type of event tree is used throughout paper V.

Lohmander (2001) describes the typical forest logistics decision situation of randomly melting snow and road problems – in connection with the issues of optimal stock levels of pulpwood, timber and truck transport solutions.

We have found that most of the optimization models used in forest logistics are deterministic. Of course, no model can cope with every aspect of risk, uncertainty or chaos. For instance, there has been a lot of research in forest economics, where the market roundwood prices have been modeled as stochastic processes (Hjorth 1996). First-order AR processes have been used in Gong (1998) and Lohmander (1987), and a first-order ARMA-process in McGough et al. (2002). However, these stochastic price approximations have not been used in the model presented in paper V.

In paper V we focus instead on weather, since it has a major influence on access by road. Furthermore, road access is one of the most essential properties of the roundwood supply chain. Internal roundwood within a company is almost always hauled some distance by trucks, at least in Sweden. In our study we have, therefore, only considered truck transport. However, the model can easily be extended to a multi-modal formulation that includes both truck and railway transport.

Another critical part in the forest logistics field is storage of roundwood, since trees are usually damaged during storage. Value losses of roundwood along the supply chain are a considerable problem for the forest sector (Persson et al. 2002). Even if studies of storage-related problems exist, as described in Persson et al. (2002), Forsberg (1999), Persson & Elowsson (2002), Hägg (1991) and Liukko & Elowsson (1999), estimation of storage costs is still a major problem for the forest sector. Unfortunately, all decisions in the roundwood supply chain are affected by storage decisions. Hence, it is necessary to optimize the whole supply chain simultaneously to get accurate results, especially when we have uncertain road bearing capacities, which are related to the water content of the road. Thus, the problem must be modeled using stochastic programming (Kall & Wallace, 1994; Birge & Louveaux, 1997).

There are also some studies that indicate substantial gains if we integrate the process at the mills with roundwood supply chain planning (Arlinger et al., 2000; Berg et al., 1995). However, these aspects of integration are not considered here, in this initial study. The roundwood supply chain problem presented in paper V, therefore, only considers the internal flow from harvesting to the mills (Figure 9.). All activities are, nonetheless, highly integrated in this chain also.

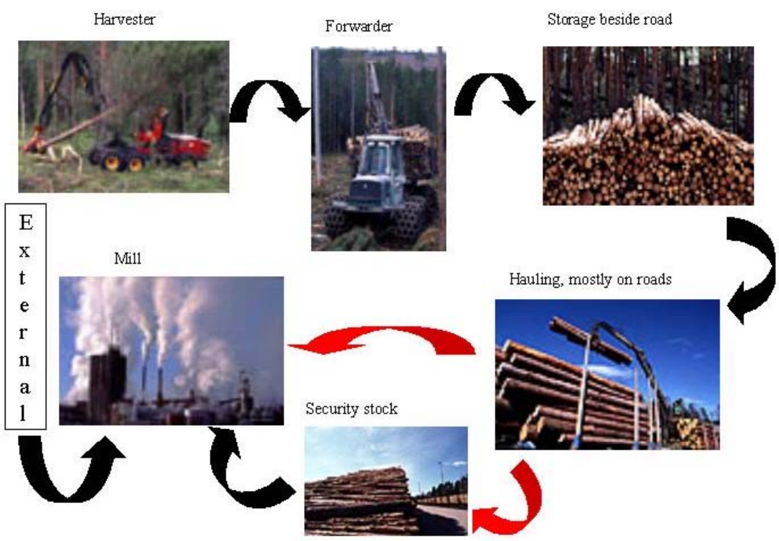

Fig. 9. The roundwood supply chain from harvest operations in the forest to the mill(s).

In the roundwood supply chain, we may consider early investments in road quality and stocks as being arrangements leading to increased flexibility, with more options available at later periods. The final transport decisions can be adaptively optimized, based on information about the true developments of snow and rain, from the event tree (Figure 7).

Although the problem size for the adaptive model in paper V will be large, due to the size of the event tree, a standard PC will have no problem solving moderately sized instances – as it is for our case, with a linear objective function and few binary variables. Furthermore, adaptive optimization is preferable (or even necessary) since weather predictions have very large errors for prediction horizons longer than a few days. In this case, deterministic scenario analysis will not be suitable. However, as mentioned in the road investment study in paper IV, in future the stochastic and the deterministic model outputs should be compared.

Summary of papers

I. Optimal forest transportation with respect to road investments

This methodological paper concerns roundwood transport on gravel roads under Swedish conditions. The forest sector in Sweden has identified road quality as being a major problem – particularly in the spring, when the ground is thawing, but also during rainy periods, which usually occur throughout the fall. The forest road upgrade problem with all assumptions is described in detail here, and it simultaneously optimizes roundwood transport and upgrading of gravel roads, over a ten-year period. The model is a deterministic dynamic network design model[2] solved with mixed-integer linear programming, since the road accessibility variables must be binary. Investments in surface roads, maintenance and construction of new roads are not included in the model, since these activities are on a different planning horizon, or cannot be decided by the company.

We test the model using deterministic scenario analysis applied to a sample problem, using a small road network located in the middle of Sweden. The Swedish forest company Holmen Skog provided harvest and road data. With a simple iterative improvement heuristic method, "near to optimal" solutions are obtained in reasonable time, for three different thawing period scenarios. Commercial software and a standard PC are used to solve the problem. In the last section, we make some concluding remarks and discuss future use of the model.

Heuristics are, as shown here, one-way of solving the problem to “near optimality” in reasonable time. Nevertheless, it is also possible to aggregate the model down to fewer time periods, or perhaps all the way down to a static model that only considers spatial aspects. In our study, we have used one time period per year over a ten-year period. However, since it is impossible to decide the road investments in advance for every year, due to the many uncertainties, fewer periods or only one time period should be used at this long-term planning level. Aggregation of the time periods will decrease the problem size substantially, since our dynamic model has ten times more variables than a static formulation. Since the model is mixed-integer, aggregation will reduce the solution time considerably.

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[2] The model in this paper must be corrected to be general. The *m* that is defined as the total demand requires time indices *t*, as well as demand node indices *j* and these should be replaced by m_{jt} in a general formulation. Nonetheless, if the demand is equal in every time period and we only have one demand node, as is the case in this paper, this new formulation adds nothing.

II. Road investment scenarios in Northern Sweden

In this paper, we apply a deterministic static network design model to a road investment problem. We solve this model with mixed-integer programming applied to the real world forest road network located around Sveg in Sweden. We only focus on the upgrading of gravel roads, hence maintenance and new roads are not included in the model, since these activities are on a different planning horizon. We use the model to calculate the optimal level of upgrading over a ten-year planning period, at the forest area owned by Holmen Skog.

The cost function for upgrading of gravel roads used by the company is described in detail, as are other assumptions. The upgrade cost function provided by the staff at the company is only a rough estimate of the real costs, and should be improved in the future.

Six different scenarios are tested using deterministic scenario analysis. These scenarios are combinations of three different lengths of the thawing period in spring, and two different objective functions. The cost of roundwood transportation has considerable influence on the solutions. Hence, we conclude that the type of objective function to be used depends on the situation, and that the entire network of roads must be optimized simultaneously, to avoid sub-optimizations.

Holmen Skog is mostly interested in the result of only optimizing the road upgrade cost. However, in this case study we have only one demand node and one assortment, due to the data input. In a more general case, it might be more relevant to optimize transportation and road upgrading jointly. The conclusion is that comparing different objective functions is valuable, and the transportation cost should be optional in a future decision support system. The forest area provided by the forest company included 440 roads.

The company provided road data and harvest volume data for the study. It is possible to obtain global optimal solutions from the optimization within a few minutes of calculation time, using commercial software and a standard PC. This is a promising prospect, since the aim is to use the model as part of a future decision support system for long-term planning of road investments.

III. Optimal road investments - A forest company case study

An extension of the deterministic static network design model in paper II is presented here. Once again, the model is solved using mixed-integer linear programming. Different scenarios applied to a real-world forest road network are considered using deterministic scenario analysis. We focus on how to optimally upgrade gravel and unpaved roads purely or partly owned by Holmen Skog during the thawing period in the spring, and periods with rain. Aspects of how to incorporate these periods into the model are considered. The problem for the forest road network of 440 roads is rapidly solved with commercial software and a standard PC.

The roundwood flow is split into two assortments, but the model allows more assortments to be used whenever suitable. The company provided us with road and harvest-related data in this study, but in future road data should be taken from the national road database.

The results indicate that the level of road upgrading should increase in the area, since this is often more profitable than the policy used today. This policy is to move the roundwood to better roads during the winter, or to store the roundwood at a larger roundwood terminal. Optimal upgrade policies for ten years are reported, with roundwood supply from a ten-year fixed harvest plan provided by the company.

Cost curves describing the average, marginal and total cost of the upgrading are calculated within a few minutes for all problem instances of the case study. An example using these cost curves is presented in the discussion to clarify the results. The use of the model in a future decision support system is discussed, and aspects of visualization are considered. A general idea of a future decision support system is presented at the end.

IV. Optimal upgrading of forest road networks: is scenario analysis an appropriate tool?

A two-stage stochastic model with binary first stage is developed to optimize upgrading of a real-world forest road network. This is an extension of the deterministic model presented in paper III. We compare the solutions from the stochastic model with solutions from deterministic scenario analysis.

Upgrade policies are provided within a calculation time of at most half a minute in the deterministic case, and within a few minutes in the stochastic case, for our case study. The modelling and calculations are performed with commercial software and a standard PC. The road network provided by the company was, however, of moderate size, and deterministic scenario analysis will be considerably faster on larger problems, since the solution time for the mixed-integer linear model is exponential. Consequently, we want to use the deterministic model in future decision aids to handle huge real-world road networks.

The deterministic model must, nevertheless, be evaluated in some way, since uncertainty is always present in the real world. The study here indicates that deterministic scenario analysis promptly provides us with near-optimal solutions to the stochastic model of acceptable quality, at least with our moderately sized problem.

We conclude that the model used here is rather insensitive to critical period length uncertainty, such as the length of the spring thaw. Nevertheless, we strongly recommend use of the stochastic model whenever possible, since the stochastic and deterministic solutions are not equal. The stochastic solution hedges against the critical period length uncertainty, and provides the decision-maker with solutions that have more options when disturbances occur.

On the other hand, when the stochastic model is too time-consuming to use directly in the decision aid, it should be used to evaluate the quality of deterministic model solutions. In this way, it is possible to view the impact of critical period length uncertainty on the solutions provided by the deterministic model used in the scenario analysis. In these cases, the stochastic model only has to be calculated when model parameters are changed, and the solution time of this model is thus of minor importance.

V. Adaptive optimization in the roundwood supply chain

A stochastic model using an event tree for optimization in the roundwood supply chain has been developed. The deterministic equivalent formulation of the stochastic model is implemented using mixed-integer linear programming. The model concerns tactical planning, and jointly optimizes harvesting, transportation, road maintenance and storage with respect to road-bearing uncertainty. However, similar models can be used at both operative and strategic levels, even if the problems differ.

Many considerations of importance to this chain cannot be predicted without errors. In such cases, it is often optimal to make flexible investments in the initial period and later on sequentially and optimally adapt decisions to the true and observed outcomes of the stochastic variables. This is called adaptive optimization, or scenario optimization. In the past, this type of problem has usually been solved with stochastic dynamic programming. Unfortunately, it is not possible to use this on our type of problem, since the state space will be far too large.

The roundwood supply chain is critically dependent on roads. Access to roads strongly depends on the current and previous levels of rain and snow. Therefore, it is natural to use different road-bearing scenarios and jointly optimize these using adaptive optimization. Many other things are, of course, uncertain; however, some of these extensions can be incorporated into future extensions of this adaptive roundwood supply chain model.

The developed model structure is explained by a sample problem. The structure can be filled with spatial information from the road network in any area, even if only near-optimal solutions will be available when the road network is very large.

A general adaptive optimization model is presented here, and tested on a sample example. The results indicate that deterministic models can probably not be used to model the roundwood supply chain correctly, since the solution will be "too optimal", with no options left when disturbances occur. Adaptive optimization should thus be used when modeling the roundwood supply chain, to provide the decision-maker with flexible solutions.

As in paper IV for road investments, however, stochastic and deterministic model solutions should be compared more broadly in the future.

Discussion

Forest road investments

The following conclusions and observations about upgrading of forest roads were presented in the Discussion parts of papers I, II, III and IV. Observations about the content of the papers have also been added here.

I. Optimal forest transportation with respect to road investments

The size (number of decision variables) of the problem solved in paper I to "near-optimality" with a simple heuristic represented approximately one-tenth of the size of a typical district within Holmen Skog (compare Figures 5 and 10).

In our example in this paper, we had 2,870 decision variables and 2,402 constraints. Of the variables, 780 were binary and the rest were continuous.

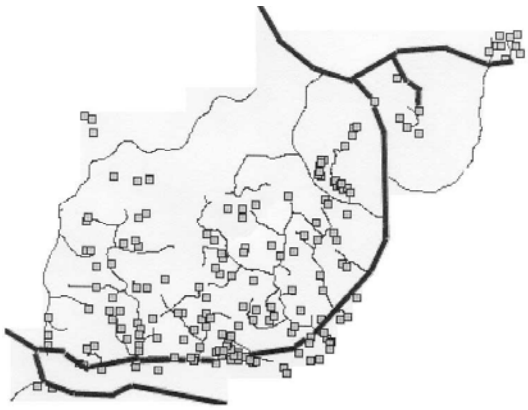

Fig. 10. The small geographical area used in paper I. Dots are harvest areas.

Even in our small example, the binary variables made it impossible to solve the problem to global optimality in reasonable time, at that time. The heuristic method used in this paper was simple and did not tell us how close the solution was to the global optimum. This was, however, a methodological paper which concentrated on an initial mathematical model that described the road upgrade in an appropriate way. Thus, the aim of this study was not development of effective heuristics.

We did, however, conclude that we would have to use some heuristic method or aggregation to solve the relevant full-scale problem in the future. The ten time periods used here could be aggregated down to only one time period. In this way, the problem size would be reduced by a factor of ten. Furthermore, the critical period length for every year would be exchanged for an average critical period length on a ten-year horizon. This is, of course, easier to estimate although the time value of money is lost.

II. Road investment scenarios in Northern Sweden

Here, the model used in paper I was aggregated down to a model with only one time period. This model was tested on the road network from a case study at a forest district owned by Holmen Skog. Scenario analysis was performed using three different critical period lengths (three, six or nine weeks on average every year). Furthermore, two different objective functions were tested, as described below.

- The first objective function minimizes the total transportation cost and the total road upgrade cost jointly.
- The second objective function only minimizes the total road upgrade cost.

Conclusions and observations from this study are presented below.

- There are major differences in the optimal solution depending on whether we minimize the total objective function, or only the upgrade cost.
- In general, when we minimize the total objective function, it will only be the roads near to the demand node that we should upgrade, in contrast to the other case where we only minimize the upgrade cost. These solutions are depicted in Figure 11 for the case with only upgrade cost, and in Figure 12 in the case where both transportation and upgrade costs are minimized. In both figures, the worst-case scenario with a critical period length of nine weeks is considered.

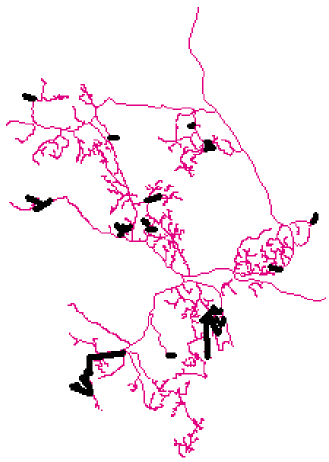

Fig. 11. Upgrading is depicted as black roads. A critical period length of nine weeks on average every year is considered. Only total upgrade costs are minimized. Note that in this case the upgraded roads are spread out over the whole area.

- The difference in optimal solution between the two scenarios increases with higher demand, because we must upgrade more roads. Furthermore, the total objective function will be affected more by the hauling cost if the demand increases (Compare Figures 11 and 12).
- The average cost of upgrading the roads is considerably lower than expected by the operative staff at Holmen Skog. Since they considered the road investment suggestions from the model output to be of good quality, this indicates that the level of road investments is to low today.

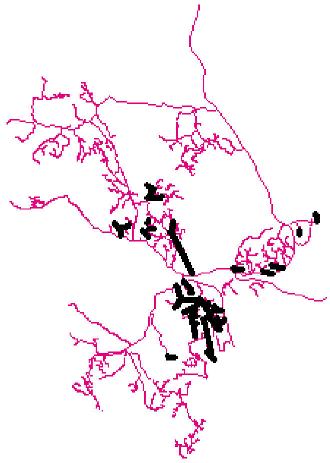

Fig. 12. Upgrading is depicted as black roads. A critical period length of nine weeks on average every year is considered. Both total upgrade cost and total transportation cost are jointly minimized. Note that in this case, the upgraded roads are located near to the demand node.

- Road investment costs should be compared to storage costs, as in Figure 2, in order to decide the optimal strategy regarding both road improvements and storage of roundwood during the critical period in the spring and rainy periods. The staff at Holmen Skog suggest, however, that these costs should be compared manually, with the help of decision support software.
- If we only minimize the cost of upgrading the roads, we should be aware of the fact that it is more important with the quality of the roads that are always accessible (A-roads) during the thawing period, since the total hauling distance will be longer if we only minimize the upgrade cost (compare the solution in Figure 11 with that in Figure 12). Hence, if we have low uncertainty about the quality on the A-roads, we should optimize only the upgrade cost. In other cases with higher uncertainty regarding quality of the A-roads, however, we should optimize the whole objective function.
- The staff at Holmen Skog consider that minimizing only the upgrade cost is the best choice at the test area in Sveg, since they are rather certain

about the quality of the A-roads, and there is only one demand node in the area considered.

III. Optimal road investments - A forest company case study

Here, the model in paper II was extended to allow assortment splitting of the roundwood flow. In the case study we considered two assortments: Spruce and Pine. However, there are no actual limitations as to the number of assortments used in the model, and a test using five assortments generated optimal solutions rather swiftly. Note that the number of continuous variables increases with the number of assortments, but that the number of binary variables that are related to the road investment level always stays fixed.

Further cost studies were performed and ideas about future development of a decision support system were presented. Some conclusions and observations are presented below.

There are two essential kinds of output from a decision support system concerning upgrading of gravel roads.

- Diagrams that describe total, mean and marginal costs. An example of the total cost is depicted in Figure 13.
- Geographical information presented as maps to visualize how to upgrade the roads (Figure 14).

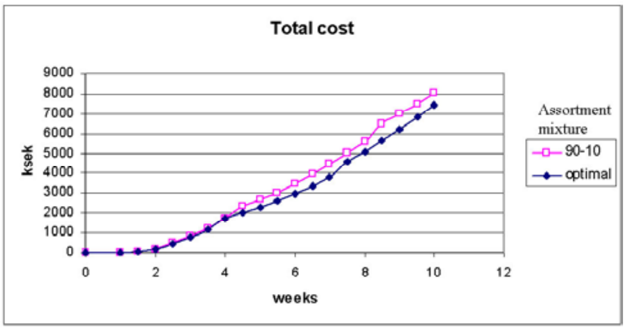

Fig. 13. The total upgrading cost depends on the critical period length, since more roads have to be upgraded to secure the fixed demand. Two cases are considered in the picture: 1: 90% Pine and 10% Spruce in the case "90-10".2: Optimal assortment mix is calculated by the model in the case "optimal". Note that the optimization has to be re-run for every dot in the diagram.

The input to the total cost diagram from the optimization forced us, in our particular case, to re-run the solver 20 times (one for every dot in Figure 13) for every assortment mixture case. Fortunately, in our test case, all the optimizations could be solved to global optimum swiftly. We concluded that the total calculation

time, with all the solutions guaranteed to be at most five per cent from global optimum were reasonable for the area.
It is thus possible to promptly generate all the information the decision-maker needs to be able to compare road upgrade costs with costs for other strategies, such as storing roundwood at a terminal.

Discussions with people responsible for road improvements in the area used in this study have indicated that decision support from the optimization model would help them to save a substantial amount of money, and also a substantial amount of time – since there would be less of a need for manual planning of road investments in the area. The study also indicates that the forest company would invest in better road quality, which would also benefit all other users.

Our final remark is that since road investments involve long-term decisions, the effect on short-term activities is very high. An "optimal" road standard will therefore affect most of the company's tactical and operative decisions, and probably save money in all parts of the roundwood supply chain.

IV. Optimal upgrading of forest road networks: Is scenario analysis an appropriate tool?

The result from the case studies in paper II and paper III was derived from a deterministic model. However, the long-term road improvement decision can easily be formulated as a two-stage stochastic model, as depicted in Figure 6. Here, results from the stochastic model were compared with results from deterministic scenario analysis. Conclusions and observations are presented below.

- Solving the two-stage stochastic model (SP) gives a solution which is different to that obtained using the deterministic model. These differences are depicted in Figure 14. In our case the option value is 412.3, making the SP solution 2.9% "better off" with respect to critical period length uncertainty, than the worst-case scenario solution. Note that the worst-case scenario solution is used for feasibility reasons in our model.
- The SP consists of the number of scenarios more continuous variables than in the deterministic model (DP). However, since the binary variables only are in the first stage, the number of them will be the same in the two models. Hence, in our example there are three times more continuous variables in the SP than in the DP – since we use three scenarios. With large-scale problems, this will make the solution time of the SP considerably longer than for the DP.
- Most of the upgraded roads are the same in the two approaches, as depicted in Figure 14. Thus, the deterministic solution of the worst-case scenario approximates the SP solution rather well.
- Our area is a forest district of moderate size as compared to many other road networks in Sweden, and in general it is not possible to solve the SP in reasonable time. In these cases, we could view scenario analysis as

being a “heuristic” method that finds the “near optimal” solution to the true stochastic programming problem in an efficient way.

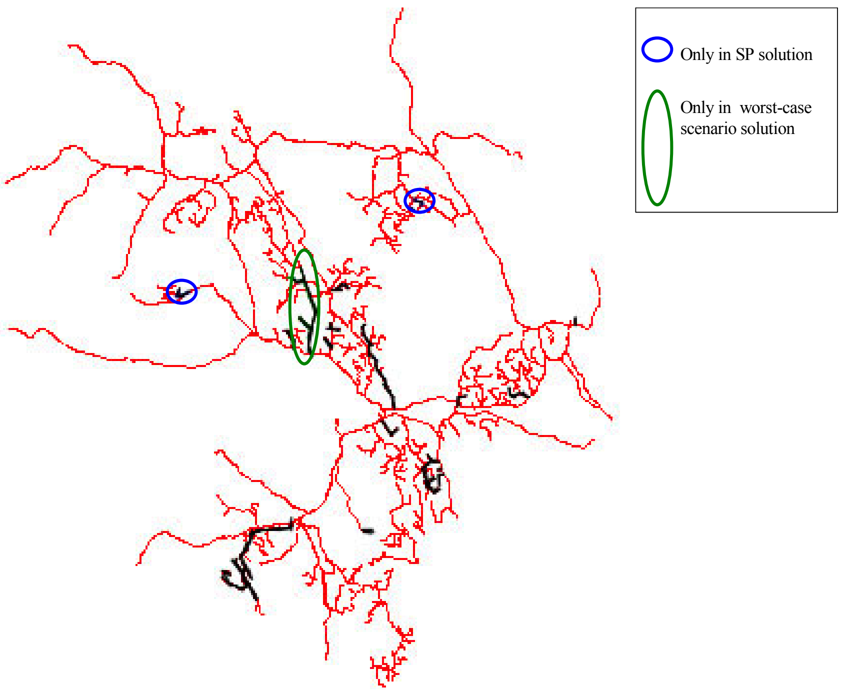

Fig.14. Solution to the stochastic model (SP) and the worst-case scenario for the forest road network, which is located around Sveg. Differences between the solutions are marked with circles and are explained in the box above.

- The possibility of obtaining good solutions swiftly is a crucial part of a decision support system. It is, therefore, necessary to use deterministic scenario analysis in the case of large-scale problems – due to time limitations. Hopefully, this will give a good approximation so that near-optimal solutions regarding uncertainty can be found promptly in such cases also.
- Evaluation of deterministic solutions should be done with stochastic programming. Our key point is that the decision-maker ought to keep in mind that deterministic scenario analysis gives solutions that are “too optimal”, with few options when disturbances occur**.** These calculations of the SP only have to be done for every road network when changing model parameters. Hence, the calculation time for the SP model is of minor importance.

The roundwood supply chain

V. Adaptive optimization in the roundwood supply chain

In the last paper, a model of the roundwood supply chain depicted in Figure 8 is presented. Aspects of uncertainty about road-bearing capacity are considered. The scenario model (Figure 6) is solved using stochastic programming. Conclusions and observations are presented below.

- It is possible to optimize all linked decisions of a relevant regional forest sector problem. For each scenario, harvesting, transport, stocks and production in forest industry mills can be optimized.
- Infrastructure and the effects of random weather conditions can be managed consistently.
- From the reported results, we conclude that risk strongly affects the optimal solutions. Hence, deterministic models will not describe the roundwood supply chain in a realistic way.
- One drawback of the event tree approach presented in this paper is that many periods, or scenarios, give us a very large model with many millions of variables. However, if we need more than five or six periods and have a large road network, we could try to use two scenarios in every period. Scenarios are needed, and two scenarios would be much better than a purely deterministic model with only one scenario, due to the hedging effect in the stochastic solution.
- Another drawback is that our model only deals with risk related to roads. Of course, many things can change randomly. However, further research should be to incorporate other aspects of uncertainty into the model.
- It is important to determine the optimal degree of detail. In many cases, it is probably better with less detailed models that take more uncertain aspects into account. Sometimes, however, a detailed deterministic model is appropriate. This has to be evaluated for every specific problem at hand.
- We have assumed the market prices to be constants. In reality, these are highly stochastic and unpredictable. It is even more important to have good roads in the presence of stochastic markets. Otherwise, the adaptive market decisions will be strongly constrained by road capacity.

Ongoing and future work

The Forestry Research Institute of Sweden (SkogForsk) is developing VägRust, a decision support system for road investments. The aim is to have the prototype finished during 2004. Papers I, II, III and IV investigate the road upgrading problem, together with old and current projects at SkogForsk and

Linköping University. Future work in this area will be devoted to more practical issues arising from the practical use of VägRust.

Managing the whole roundwood supply chain is a more challenging task and has to be more extensively studied in the future. One current project at Mid-Sweden University is to further develop the model presented in paper V in many directions, as described in Hultqvist & Olsson (2004a, 2004b). Some of these extensions are presented below.

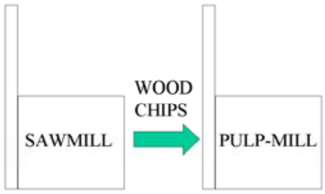

Fig. 15. Wood chips are transported from sawmills to pulp-mills using special trucks.

- The roundwood supply chain problem also incorporates the flow of wood chips from sawmills to pulp-mills (Figure 15).
- Roundwood can be bought or swapped with other operators (Figure 16).
- We try to integrate the process at the mills with roundwood supply chain planning as much as possible (Figure 16).
- The model now has a quadratic harvest cost, making the it mixed-quadratic.
- Many other constraints and fixed costs have been added to the model.
- Railway transportation can be managed, making the problem multi-modal.
- Results from stochastic and deterministic models will be evaluated and compared.
- Storage nodes can be handled in general (not only for three time periods) through a multi-commodity network (Rardin, 1998).
- The storage costs are now time-dependent, but still linear with respect to the volume, as depicted in Figure 17.

The future aim is to the test this extended model on some real-world cases, in the same way as the road investment problem presented in papers I, II, III, and IV. To be able to perform fast computing and to test many different optimization algorithms, parallel computing will probably be necessary. Scenario models are well-suited to parallel implementations, and some algorithms already exist, as described in, for example, Linderoth & Wright (2003) and Birge & Louveaux (1997).

Lastly, cost function parameters based on empirical investigations are often hard to find. Some storage cost functions, in particular those reflecting the costs of quality losses in roundwood of different assortments, must be determined for different weather conditions and periods. This is one of the key issues for future research. Without this information, we can never determine the true optimal road qualities, stock policies and truck scheduling solutions. Research into the topic of storage costs is, therefore, essential for future progress in the research area of roundwood supply chain optimization.

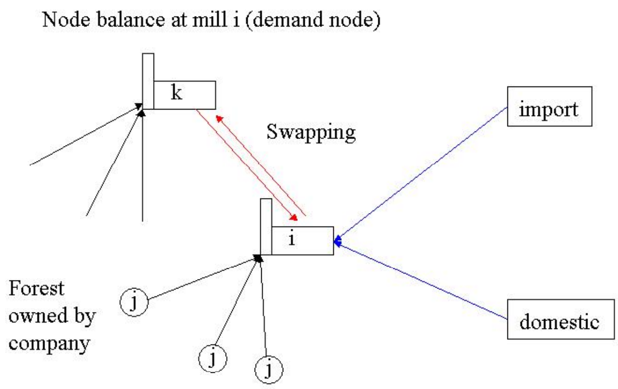

Fig. 16. In the future, we concentrate on the supply of raw material to mill I. The internal roundwood supply chain considered in paper V is only the "forest owned by the company"-part of this highly integrated system.

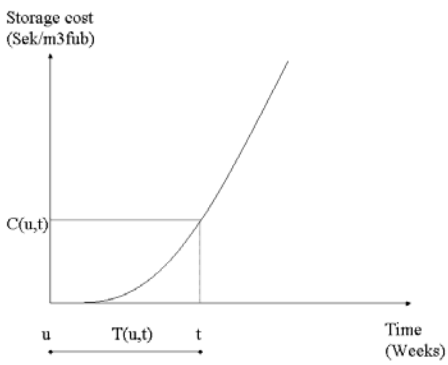

Fig. 17. The storage cost C(u,t), where u is the start time and t is the end time, is usually non-linearly dependent on the storage time T(u,t), but under some assumptions, linearly dependent of the volume. Note that the cost function above is only an example of how a storage cost function might behave. Many parameters affect this storage cost, and no general cost functions are available at present.

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