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Supply chain optimization in the forest industry

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Abstract

The scope of this thesis is modelling and solving large-scale planning problems in the supply chain within the forest industry. Five research papers are included, the first three of which focus on the modelling, and the last two on the solution methods. All problems included are tactical multi-commodity problems expressed as mixed integer programming (MIP) models. The work has been done in collaboration with two Swedish companies within the forest industry.

In Paper I, a problem concerning the supply chain of forest fuel for Sydved Energileveranser AB is modelled and solved. We study the problem of deciding when and where forest residues are to be converted into wood chips, and how the residues and chips are to be transported and stored in order to satisfy energy demand at heating plants. The company has long-term contracts with forest owners and saw mills. Decisions in the model include whether or not additional harvest areas and saw mills are to be contracted and which terminals to use. The planning horizon is one year and monthly time periods are used.

Papers II–V are based on planning problems at Södra Cell AB. The planning horizon is normally one year. Papers II–III consider only one time period. In Paper II the supply chain from pulp mills to customers is modelled and the combined problem of deciding terminal locations and which ship routes to use is studied. Shipping vessels chartered on short or long term are used to transport products to terminals in Europe. From each terminal, the products are transported to customers by truck, train, or a combination of both. In addition, trains and trucks can be used for transports directly to customers from mills. In Paper III the entire supply chain, from harvest areas to customers, is considered. Decisions included are transportation of raw materials, production mix, the distribution of pulp products, and the selection of potential orders and their quantities at customers. The ship routes are considered as flow links.

In Papers IV–V the problems in Papers II–III are combined into one model and several time periods are used. Lagrangian heuristics based on Lagrangian decomposition are used as solution methods in both papers. In Paper IV, the approach leads to subproblems for each time period, whereas in Paper V, another approach that results in subproblems for different parts of the supply chain is developed.

All models are based on real data from the companies. The models are detailed and describe the problems accurately. The solution methods are developed such that the solution time is kept within practical limits. Results from Papers II–III have been used by Södra Cell AB to support the change of the terminal structure as well as in budget planning.

Optimering av logistikproblem inom skogsindustrin

Sammanfattning

Denna avhandling presenterar matematiska modeller och lösningsmetoder för optimering av olika logistikproblem inom skogsindustrin. Vi studerar försörjningskedjor för skogsbränsle och massaproduker, och beaktar den årliga planeringen i syfte att optimera flödet.

Det första problemet behandlar skogsbränsle och är ett samarbete med Sydved Energileveranser AB. Råmaterial i form av grenar och toppar från avverkningsplatser ska flisas och transporteras till värmeverk, eventuellt via terminaler. Det finns möjlighet att flisa både i skogen och på terminaler. Biprodukter från sågverk kan också användas som råmaterial. Vid behov kan utbudet av råmaterial utökas genom att fler avverkningsplatser och sågverk kontrakteras. Värmeverken har en efterfrågan, angiven i kWh per månad, som ska uppfyllas. Exempel på beslut som ska tas är var flisning ska ske, om nya avverkningsplatser ska kontrakteras, var lagring ska ske, samt hur och när skogsbränslet ska transporteras.

Nästföljande problem behandlar massaprodukter och är ett samarbete med Södra Cell AB. Olika sorters massaved från skogen och biprodukter från sågverk utgör råmaterial för produktion av massaprodukter. Råmaterialet transporteras till massabruk för tillverkning enligt specificerade recept. De färdiga produkterna transporteras sedan med fartyg till terminaler i Europa. Från terminalerna transporteras produkterna vidare till pappersbruk, vilka är företagets slutkunder. Massaprodukterna transporteras i vissa fall med lastbil eller tåg direkt från massabruken till kunderna. Efterfrågan är angiven inom vissa gränser i olika order. Vissa order är fasta, vilket innebär att dess efterfrågan måste uppfyllas, medan andra order är fria. Exempel på beslut som ska tas är vilka bruk olika produkter ska produceras på, hur många och vilka terminaler som ska användas, samt hur transporterna ska utföras för att ge bästa resultat.

Utifrån ovanstående beskrivningar har matematiska modeller formulerats. Genom att lösa dessa kan vi få svar på logistik- och transportfrågorna och ett optimalt flöde kan hittas. För att lösa modellerna har kommersiell programvara använts. Heuristiker och mer avancerade optimeringsmetoder har också utvecklats i syfte att producera bra lösningar snabbare.

Papers included

The following five papers, which will be referred to in the text by Roman numerals, constitute the basis for the thesis.

Paper I: **Supply chain modelling of forest fuel**
Helene Gunnarsson, Jan Lundgren, and Mikael Rönnqvist
European Journal of Operational Research, 158 (2004) 103–123.

Paper II: **A combined terminal location and ship routing problem**
Helene Gunnarsson, Mikael Rönnqvist and Dick Carlsson
Journal of the Operational Research Society, 57 (2006) 928–938.

Paper III: **Integrated production and distribution planning for Södra Cell AB**
Helene Gunnarsson, Mikael Rönnqvist and Dick Carlsson
Journal of Mathematical Modelling and Algorithms, 6 (2007) 25–45.

Paper IV: **Solving a multi-period supply chain problem for a pulp industry using Lagrangian heuristics based on time periods**
Helene Gunnarsson and Mikael Rönnqvist
Manuscript in preparation.

Paper V: **Solving a multi-period supply chain problem for a pulp industry using Lagrangian heuristics based on physical stages**
Helene Gunnarsson and Mikael Rönnqvist
Manuscript in preparation.

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Introduction and overview

Introduction and overview

We start by giving a short introduction to the field of supply chains. Thereafter the forest supply chain is in focus and different planning levels are introduced. Then some approaches of optimizing the supply chain are presented. Last the papers included in this thesis and their contributions are described.

Supply chains

A supply chain starts with the supply of raw materials for the products, passes through one or several steps for manufacturing, storing and distribution, and ends at the customer for the final products. Examples of supply chains are often presented in a network form. A simple example of a supply chain is given in Figure 1.

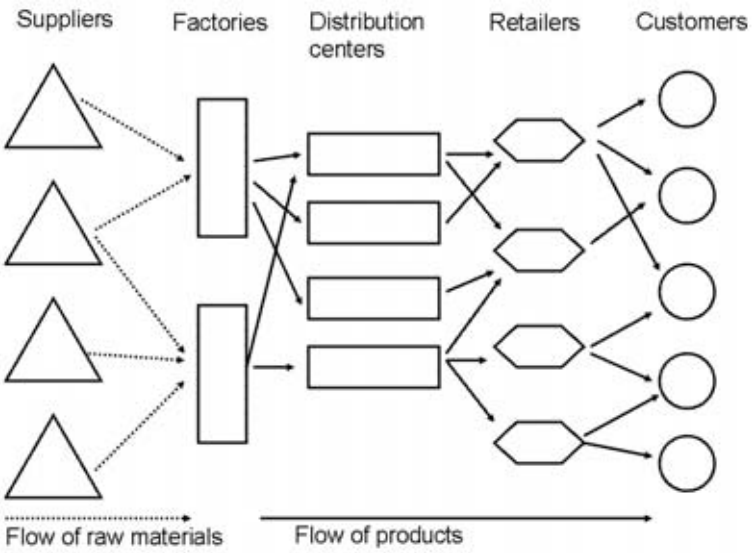

Figure 1: Illustration of a general supply chain.

Since the 1990's supply chain management (SCM) has been very popular and useful concept in industrial planning. The SCM can be viewed from different perspectives, see O'Brien et al. [54]. One perspective is the industrial organization economics considering market structure and its importance. The other perspective is the analytic modelling of supply chains focusing on finding good planning measured for example in costs. An attempt to combine these perspectives in order to benefit the overall planning of the SCM is presented in O'Brien et al. [54].

The area of SCM can also be divided into two parts, the integration of organi-

zational units and the coordination of flows, see Stadtler [73]. The aim of both parts is to provide customer service and to be competitive in order to increase profits. In order to make the coordination of flows more efficient, advanced planning systems (APS) are used. Ingredients for operating the supply chain regarding the coordination of flows, successfully, can be, for example, operations research (OR) and logistics, see Stadtler [73].

A basic description of supply chain modelling is found in Shapiro [69]. A more detailed description of industrial cases can be found in Stadtler and Kilger [74]. Examples of application in the textbook are a case of computer assembly by Kilger [42] and a case about food and beverages by Wagner and Meyr [77]. The efficiency of the logistics operations efficiency is crucial for the successful management of a supply chain. It is important to view and understand the overall supply chain to be able to make decisions that can imply, for example, shorter lead times and less need of safety stocks. A survey of SCM with regard to Swedish manufacturing firms, can be found in Olhager and Selldin [55]. The paper investigates the supply chain management strategies and practices in a number of companies.

We will from now only consider the supply chain including flow of materials. The focus will be on analytic supply chain modelling in general and forest supply chains in particular.

Forest supply chains

An illustration of the supply chain valid for forest products in Sweden can be studied in Figure 2, below.

The activities that have to exist in order to get the correct amount of raw materials from the forest without reducing future harvest possibilities, are planting, cleaning, thinning, and harvesting. The assortments obtained from forest raw materials can be classified according to their use. Saw logs, pulp wood, and forest residues are the major parts of the assortments. Each part can be further divided into several subgroups according to their qualities and dimensions.

After harvesting, timber is transported to saw mills. The timber can also be transported to terminals for storage before transportation to the saw mills. Similar conditions hold for pulp wood, it is either transported directly to pulp mills, or is taken via terminals for intermediate storing. The harvesting leaves some forest residues in the form of tops and branches. The residues are left for around a year in the forest and are then chipped. Then, after storage at terminals (if necessary), the residues can be transported to heating plants. Byproducts from saw mills, such as chips, are transported to pulp mills and heating plants for further use. The making of pulp also produces byproducts, such as bark. These byproducts are used as fuel at the pulp mill or at heating plants. The final pulp products are transported to paper mills to make paper products. The last transportation (which is not included in the illustration), is transportation

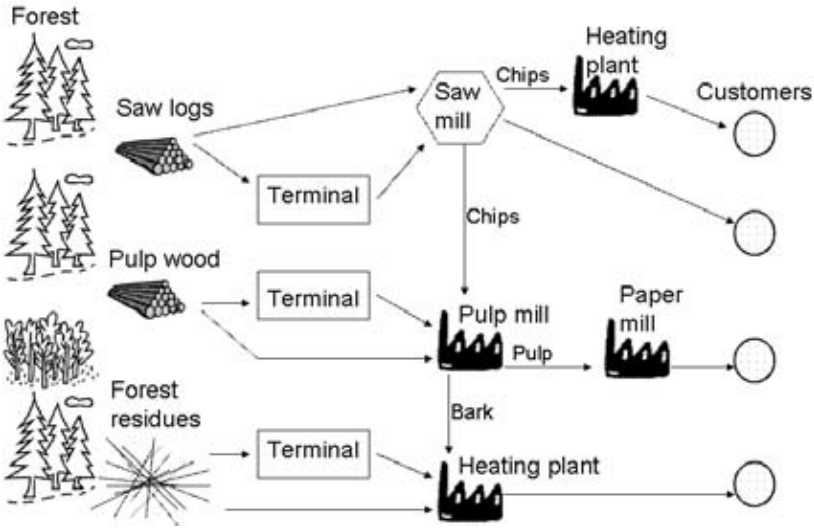

Figure 2: Parts of the forest supply chain.

from the saw mills, paper mills, and heating plants to the final customer or to distribution nodes. Excluded from the illustration above is also the transportation of wood ashes from heating plants back to the forest. The wood ashes are dispersed over the ground to improve the quality of the soil.

Planning levels

There are different planning levels, which depend mainly on the planning horizon, to consider. Different planning levels and horizons have different needs for supporting tools. Even if the number of computer based supporting tools is increasing, most of the planning work is still done manually. These different planning levels are described, for example, in Rönnqvist [64] and Weintraub and Romero [80]. The strategic level often describes decisions that concern several years or decades. Strategical decisions include investment planning and infrastructure planning, for example, road building. Tactical planning is often connected to annual decisions, but it could be for shorter or longer periods, depending on the problems considered. Tactical decisions include, for example, road upgrading, annual production planning related to the budget processing, route structure and equipment utilization. The last level to be mentioned is operative planning, which could span over a couple of months or involve daily planning. Examples of operative decisions are detailed production planning and truck dispatching. The differences in time for each level depending on the type of problem are not clearly defined. We will now describe the planning levels related to the supply chain in the forest industry. We start by harvest problems

and continue with routing problems. Finally, planning levels in production are discussed.

Harvesting problems have other horizons regarding planning levels. Here, operative planning includes decisions for months, tactical planning could be from half a year to a few years, and strategical planning involves decisions for several decades. The long horizons within harvesting of course are due to the long rotation times of trees. MEDFOR, a planning tool for strategical decisions in a horizon of 50 years, is described in Epstein et al. [20]. Another model for strategical harvest planning can be found in Gunn and Rai [25]. A system based on simulating conditions in forestry is Indelningspaketet, which is used in Sweden, primarily for the strategical planning of harvesting over large harvest areas [39]. This system is intended to be an aid in decision operations, such as how much to harvest each year, proportions of thinning and final harvesting, and in which order to work the areas. For making tactical decisions, the OPTIMED tool, which is a tool for support harvest planning for a period of two to five years can be used, see Epstein [20]. Harvest scheduling, road access and adjacency constraints are considered simultaneously in Richard and Gunn [62]. They address the tactical planning problem with a tabu search method. The design of the tabu search method is further discussed in Richards and Gunn [63]. A harvest planning model for the short term can be found in Karlsson et al. [40], where a planning period of four to six weeks was considered and harvest schedules for the different harvest crews were decided. Other models for short term harvest planning can be found in Epstein et al. [19]. A model integrating long term harvest planning with short term harvest planning can be found in Nelson et al. [52].

With regard to routing problems, the operative level often involves daily decisions about the routes. The tactical level in routing problems can be from two weeks up to a month, and the strategical level considers decisions of one year or longer periods. In Weintraub et al. [78], an operative and computerized system to support daily truck scheduling decisions is developed, and the system has been implemented in some of the largest forest firms in Chile. Another approach to the problem of optimizing daily transports within forestry is used in Palmgren et al. [56], where the aim was to find efficient routes for all the trucks involved. Several studies have been made within this area, for example, Rönnqvist and Ryan [65].

Within the area of production planning problems, the levels often depend on the products. Usually, operative planning in production problems depends on the use of working shifts, times, or daily planning. Tactical planning is often annual, and the strategical level concerns several years. An integrated optimization system of the bucking, sawing and planing processes, CustOpt, is presented in Lidén and Rönnqvist [46], where the aim was to get chain forestry - saw mill - planing mill to work in a more customer oriented manner. CustOpt is a support system on a tactical level with a three months planning horizon [46]. Problems regarding the sawing of the logs at saw mills can be found in Todoroki and

Rönnqvist [75, 76]. The logs should be sawed in such a way that the amount of residue is minimized. Trying to adjust the sawing with regard to customer demand would to a great extent both save time and raw materials. Another similar problem can be found in Reinders [61], where a decision support system which focuses on tactical planning was developed.

Optimization of supply chains

In the past, firms tried to optimize parts of their supply chain separately. Nowadays approaches integrating different parts of the supply chain have become popular. The basic ideas behind most of the solution methods in the papers described below, can be found in Wolsey [81].

One way of describing the supply chain is to focus on the different activities involved, such as production and distribution. Reviews of the integration of production and distribution can be found in Sarmiento and Nagi [66] and Selçuk Erengüç [68]. In Chang and Lee [10], a two-stage problem is defined, one problem for the manufacturer and one for the distributor. Two practical approaches were applied to solve the logistic scheduling problem, the forward approach and the backward approach. The problems are solved sequentially using a heuristic method. Another heuristic method used for solving similar problems can be found in Park [57]. A heuristic consisting of two phases is introduced. In the first phase, a tentative production and distribution plan is established, while in the second, an improvement of the plan is attempted. Integrated design methodology for production and distribution based on the Benders decomposition can be found in Dogan and Goetschalckx [18] and Cordeau et al. [14]. Some types of integrated production and distribution problems of reasonable sizes can be solved directly using CPLEX, see Dhaenens-Flipo and Finke [17]. In Jayaraman and Pirkul [38], a heuristic which utilizes linear programming techniques as well as results from the Lagrangian relaxation procedure in order to solve an integrated production and distribution problem, is presented. The supply chain of a nursery company is optimized in Rantala [59], where a capacited MIP problem for solving an integrated production-distribution problem for a Finnish company is presented. The main decision to consider is if the company should expand or closure its facilities. The original model is strategical, but by applying applicable constraints, the model can also be used for solving tactical and operational level problems.

Another way of describing the supply chain is to focus on different kinds of decisions at different levels. In Shen [70], the strategical level is connected to the supply chain design phase and after these kinds of questions have been answered, the focus shifts to decisions at tactical about operational levels such as inventory management, and decisions on supply and demand distribution. There exist several integrated models of any two of the three important supply chain decisions; location, routing and inventory [70]. A survey of models integrating the location and routing decisions can be found in Salhi and Nagy [51]. They

propose a classification scheme and look at both exact and heuristic algorithms. Other reviews of the location-routing problem can be found in Balakrishnan et al. [2] and in Min et al. [49]. Most of the earlier studies focus on heuristic methods. A location-routing model which considers several kinds of products, a multi-commodity model, is presented in Bookbinder and Reece [4].

The integration of inventory and routing (IR) involves inventory management and vehicle routing decisions. A survey of IR models is provided by Kleywegt et al. [43]. They present a classification of the IR models based on the type of demand, fleet size, length of the planning horizon and the number of visited demand points on a vehicle trip. The research contributions of the different models are also presented. Other more recent reviews can be found in Kleywegt et al. [44]. A logistical overview of inventory routing problems is given in Moin and Salhi [50]. They classify the research according to the planning horizon employed in the models; single period, multi period and infinite horizon. Christiansen and Nygreen [11, 12] used a column generation approach for solving a combined ship routing and inventory problem. A real ship planning problem, including both inventory management and routing with time windows is presented in Christiansen [13] and solved by approaching a Dantzig-Wolfe decomposition combined with branch-and-bound. Campbell and Savelsbergh [6] presented a decomposition approach for an inventory-routing problem. A two-stage approach based on the decomposition of the set of decisions and a combination of branch-and-bound and heuristics were used as solution methods.

Models integrating location and inventory decisions can be found in Shen et al. [71] and Daskin et al. [15]. The model presented in Daskin [15] is a non-linear mixed integer programming model and Lagrangian relaxation is proposed as a solution method together with heuristics in order to find feasible solutions. The model presented in Shen et al. [71] is solved using a column generation method. A review of integrated location and inventory models of a smaller extent can be found in Daskin et al. [16]. They also present a basic model for the integration of location and inventory decisions.

The most common ways to express the objective function in supply chain models, are in cost and profit units. There are other options to express the objective function. Relevant criteria to consider can be lead times and storage safety levels. Li and O'Brien [45] presented a model which measured the quality of a supply chain considering four criteria; profit, lead time performance, delivery promptness and waste elimination. The model analyzes the performance at two levels, the chain level and the operations level

A description of the supply chain in the forest from the perspective of Chilean forestry firms can be found in Weintraub [79]. The use of models and computer systems related to each physical stage in the chain is discussed as well as the coordination between stages. In Epstein et al. [20] a more detailed description of the OR system in the Chilean forest is presented. A general overview of OR work within forestry can be found in Martell et al. [48] and Rönnqvist [64]. In

Weintraub and Romero [80] the OR models in forestry are compared to those in agricultural. They concluded that more models managing the entire supply chain in the forest are to be expected in the future. With regard to Swedish conditions, several wood flow problems in forestry are described in Carlsson and Rönnqvist [9].

The supply chain of wood fibre flow is studied in Carlsson et al. [7], where an overview of the planning problems is presented in a matrix. A description of OR tools used in practise is also provided as well as trends in the field. Supply chain management in the pulp and paper industry can be found in Carlsson et al. [8]. The overall supply chain and its participants are described, and the need for more information and decision support system is discussed.

Daily supply chain decisions regarding production and distribution of pulp products for the Swedish pulp company Södra Cell AB, are optimized in Bredström et al. [5]. The planning horizon is three months and optimal production length for each pulp product is decided as well as storage levels and distribution schemes. A MIP model is developed, and then solved using branch and price, where the subproblem is a shortest path problem.

In Philpott and Everett [58] a model for the optimization of the supply chain in the paper industry is presented. The model is a large MIP model known as the Paper Industry Value Optimization Tool (PIVOT). The model finds an optimal allocation of supplier to mill, product to machines, and machines to customer, and also the details in the supply chain are optimized.

Although many models have been developed in this area, there is still more research to be done. The tactical models for the entire supply chain of forest fuel and pulp products presented in this thesis contribute to the research field of optimization of supply chains.

The Papers included

In this section we start by giving an overview of the included papers. We will continue by summarizing the papers in chronological order. Then the contributions will be presented and finally some suggestions for future research are presented.

Overview of the Papers

The main purpose of this thesis is to model large problems within the forest industry, and to solve them in reasonable time using different solution methods.

The creation and development of the mathematical models have in all papers followed the operations research (OR) process. The OR area is wide and there exists many books covering the subject, e.g. Bertsimas and Tsitsiklis [3], Wolsey [81], Ahuja et al. [1] and Rardin [60]. The OR process is illustrated in Figure

3.

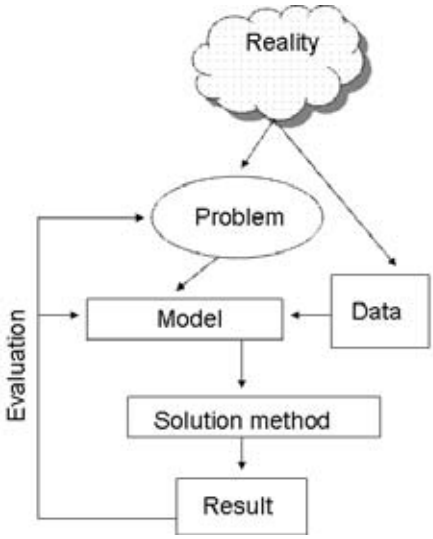

Figure 3: The OR process.

To define a relevant problem has been an iterative process in close connection with the planners at the companies. All the papers consider the supply chain problem in the Swedish forest industry. Paper I describes the supply chain of forest fuel and Paper II - V consider the supply chain of pulp products. The problems discussed in the papers are multi-commodity problems, which means that several products are included. The problems considered are on a tactical level and the planning horizon is normally one year. After the problem is clearly defined, a model is to be formulated.

In the modelling process several issues have to be taken into consideration. Questions of how to express limitations and include decisions are addressed. The models often have to be reformulated due to changed or updated conditions regarding the problems. The models in all papers are large and detailed. The modelling language AMPL is used for all model formulation in the papers. All included models are mixed integer programming (MIP) models and they include continuous and binary variables.

After the models are stated, all data is to be collected. This required time and effort in all models due to their sizes and the difficulties to get the adequate data. It is very important to make sure that the data is correct. The models become useless if wrong data is used.

All of the included problems are solved using the commercial program CPLEX directly or as a module in developed methods. In Papers I and II heuristics based on the linear programming solution are developed. In Paper IV two variants of a heuristic based on decomposition in time are used and finally in Paper V a

heuristic based on decomposition of parts in the supply chain is used.

The large sizes of the models in Papers IV–V, motivated developing of more advanced solution methods. For that reason, different variants of Lagrangian heuristics based on Lagrangian decomposition are developed. The idea of a Lagrange relaxation is to relax constraints and move them together with a multiplier to the objective function. General presentations and early papers describing Lagrangian heuristics can be found in Geoffrion [23] and Fisher [22].

The Lagrangian decomposition method is presented in, for example, Guignard and Kim [24] and Näsberg et al. [53]. The idea is to duplicate variables and relax the equality constraints which say that they should have the same value. This will lead to the division of the problem into subproblems; for each time period in Paper IV and for each physical stage in the supply chain in Paper V.

The last step of the OR process is the analyzing of results. The reasons to strange results can be several. The data can be incorrect or the model can have been formulated in an inappropriate way. Conditions that no one involved in the model process thought of can appear. It is important to discover the source of unexpected results in order to be able to use the model in a correct way. The results of Papers I–III have been analyzed to varying extent. The models in Papers II and III have been used and developed at the company Södra Cell AB.

An overview of the circumstances regarding the papers is presented in Table 1. Different properties that represent the problems in the papers are given. Examples of properties are conditions of the supply and the demand, time periods included and the sizes of the problems. The aim with Table 1 is to make the comparison of papers easier to the reader.

Table 1: Overview of the properties of the problems and models in the papers included in this thesis.

Properties	**Paper I**	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Company	Sydved Energi-leveranser AB	Södra Cell AB	Södra Cell AB	Södra Cell AB	Södra Cell AB
Product	Forest fuel	Pulp	Pulp	Pulp	Pulp
Number of products	6	30	18	5-19	5-19
Number of time periods	12	1	1	4, 12	4, 12
Decomposition	No	No	No	Yes	Yes
Heuristics	Yes	Yes	No	Yes	Yes
Production	Yes	No	Yes	Yes	Yes
Terminal location	Yes	Yes	No	Yes	Yes
Focus	Model	Model	Model	Algorithm	Algorithm
Demand	Fixed	Fixed	Within limits	Within limits	Within limits
Eligible demand contracts	No	No	Yes	Yes	Yes
Eligible supply contracts	Yes	No	No	No	No
Objective	Min. costs	Min. costs	Max. profit	Max. profit	Max. profit
Modes of transportation	Trucks	Trucks Trains Vessels Barges	Trucks Trains Vessels Barges	Trucks Trains Vessels Barges	Trucks Trains Vessels Barges
Routes	No	Yes	No	Yes	Yes
Number of constraints	63,122	11,309	37,165	71,289 – 274,217	71,289 – 274,217
Number of binary variables	10,201	2,449	174	675 – 825	675 – 825
Number of continuous variables	494,911	422,796	2,019,384	370,811 – 3,489,036	370,811 – 3,489,036

Below, the papers included in this thesis are summarized. We start by describing the problems and modelling issues. Then the sizes of the problems are given, and finally the developed solution methods are presented.

Paper I: Supply chain modelling of forest fuel

The aim of this paper is to formulate and solve an optimization model describing the planning problem for a company supplying forest fuel. The test data is from the Swedish company Sydved Energileveranser AB. The planning horizon is one year and the period is divided into 12 time periods (months).

The supply sources consist of a number of harvest areas and saw mills. They can either be owned by the supplying company or be possible to contract. The forest residues in contracted harvest areas can be made available if the company enters into a contract with a supplier of residues. To contract a saw mill implies taking care of byproducts in the form of sawdust, bark, and dry chips, continuously over the year. After the harvesting, a lot of forest residues, consisting of forest residues from hardwood and softwood, as well as decay damaged wood, are left in the harvest area. The residues have to be forwarded and removed from the area. Before using the residues as fuel, they have to be chipped. The chipping can take place either in the forest or at terminals. Figure 4 gives an overview of the problem. The division of the terminals into two sections is meant to show the storage of non-chipped and chipped forest residues, respectively.

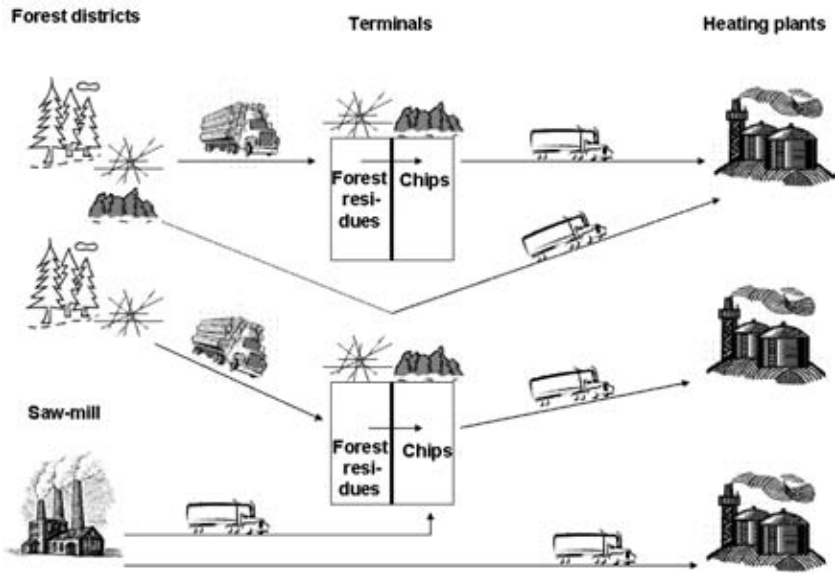

Figure 4: An illustration of the supply chain problem in Paper I.

The demand at the heating plant is specified in kWh, in contrast to the supply

which is given in m^3. Therefore, the forest fuel has to be converted into energy values. The energy value depends, for example, on the moisture contents in the forest residues.

The choices of chipping possibilities together with the conversion into energy are new challenges, that are to be considered in the modelling processes. A mixed integer programming (MIP) model is formulated, and then solved using CPLEX. In addition, a heuristic method based on the LP solution is developed. The basic case includes 494,911 variables, whereof 10,201 are binary and 63,122 constraints. Several other cases, besides the basic case, are studied and evaluated.

Paper II: A combined terminal location and ship routing problem

The aim of this paper is to formulate and solve a model, that includes both location decisions and routings. This is a case study from Södra Cell AB, one of the world's leading manufacturers of market pulp [72]. The problem described is how to transport and distribute pulp products from pulp mills to customers as cheaply as possible. Figure 5 gives an overview of the supply chain.

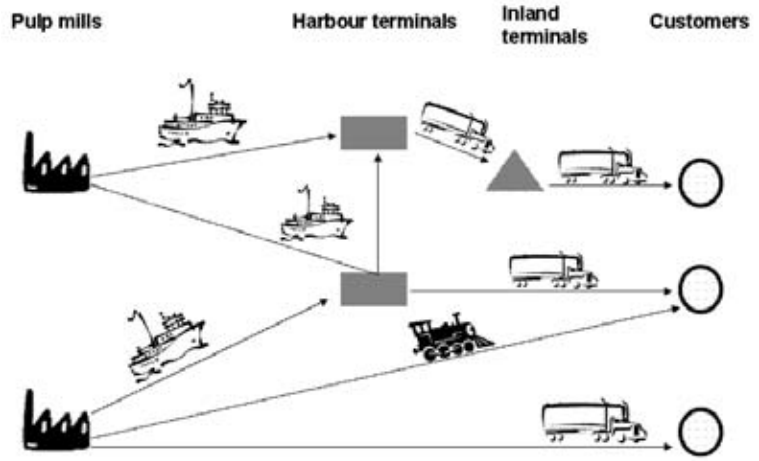

Figure 5: Illustration of the supply chain in Paper II.

Most of the pulp products are transported from a pulp mill to the nearest harbour and then further by ship to a harbour terminal outside Scandinavia. All of the customers located in Scandinavia are supplied by train or truck transportation. Trains and trucks are also used to supply some of the customers outside Scandinavia.

The pulp can be transported from the harbour terminals to inland terminals. Barges are often used for this transportation, but trains and trucks can also

be used. The transportation from the harbour and inland terminals to the final customer is made by train and truck. Three vessels chartered long term, so-called TC-vessels, are used. The routes used by the TC-vessels are divided into direct routes, called A-routes, and composite routes, called B-routes. The A-routes go from one pulp mill to one terminal and the B-routes visit several places. In addition, vessels chartered short term, spot vessels, are used from a pulp mill to one destination.

Due to the large size of this problem, only one time period is used. One of the difficulties and challenges in modeling this problem is that we need to integrate long term decisions on terminal usage with short term decisions on which routes to choose. Some terminals are connected to few customers with small demands. These terminals need to get deliveries throughout the year in order to satisfy their orders. Only one direct delivery using a A-route is not practical. Since we only have one time period we can model a continuous delivery through the use to B-routes. The smaller the terminal is, the larger proportion of B-routes is needed. On the other hand, if the terminal is large we can use A-routes with direct deliveries from the mills. Since the B-routes are more expensive, we need to link the proportion of B-routes against the size of the terminal. Otherwise all flow would be using A-routes. Therefore different levels on the terminals are introduced. The levels are modeled through binary variables and only one level can be chosen. The levels are coupled to the received flow at the terminal. High levels mean large flow and more deliveries on A-routes are accepted. Otherwise, B-routes, must be used in a particular proportion relating to the level.

The combined terminal location and ship routing problem is formulated in an MIP optimization model. Five different cases, which are modifications of the basic case, have been tested and evaluated. The basic case includes 425,245 variables, whereof 2,449 are binary. The number of constraints included is 11,309. The solution approach is to use CPLEX directly and to use heuristics based on the LP solution to find a good solution in an acceptable time.

Paper III: Integrated production and distribution planning for Södra Cell AB

Paper III is related to Paper II. The problem this paper considers is the whole supply chain from the forest districts to the customer. Different kinds of raw materials originating from hardwood or from softwood, are transported by trucks from the forest districts to the pulp mills. Pulp products are produced according to different recipes at the pulp mills. The composition and usage of raw materials are restricted within certain limits. The choice of using different recipes at different pulp mills creates alternatives. A change over cost is connected to each alternative and only one of the alternatives can be chosen. Another difference from the Paper II is that all of the terminals are fixed, meaning that we do not include any choice of terminals. The reason why this problem includes fewer terminals is that Södra Cell AB has changed their policy regarding the number

of terminals to use. The model does not include routes in the same sense as before. In order to simplify the problem, the direct routes are in this paper considered as direct flow without restrictions.

The demand, specified in orders, is given within certain limits. The orders can be fixed, meaning that related demand have to be fulfilled, or the orders can be free. Contracts are specified by orders connected to them. The choice of accepting a contract or not have to be made. Accepting a contract means that the demand in all included orders have to be fulfilled within the given limits. An overview of the problem is illustrated in Figure 6.

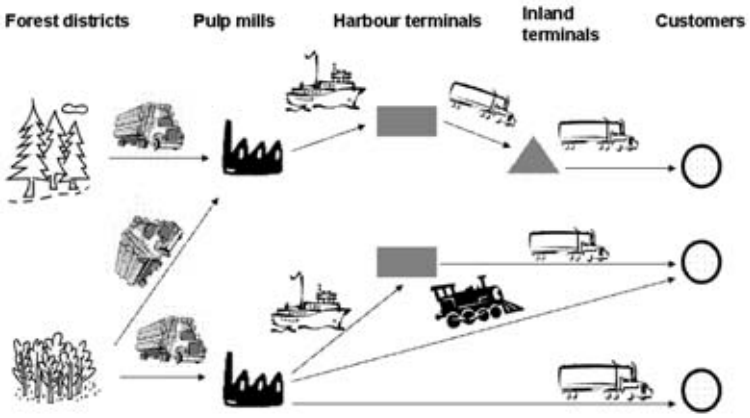

Figure 6: Illustration of the supply chain in Paper III.

An MIP model for the entire supply chain problem is presented and five different alternatives are tested and evaluated. The complete problem, including all alternatives, includes over 2,000,000 variables, whereof 174 are binary. The number of constraints is 37,165. The model was used to support the annual budgeting for 2005-2007.

Paper IV: Solving a multi-period supply chain problem for a pulp industry using Lagrangian heuristics based on time periods

The problem described in this paper is a combination of the problems considered in Paper II and Paper III. The mathematical model developed includes all kinds of routes, (A-routes, B-routes and spot trips), as well as terminal location and production of pulp products. The components which have been added compared to the previous models of the supply chain are the time periods and the storage possibilities. The raw materials can be stored in the forest. To a limited extent, The pulp products can be stored at the pulp mills and at the terminals. All of the pulp products have to be distributed during the planning horizon. Different

demand structures are taken into consideration. The supply chain for Södra Cell AB in is illustrated in Figure 7.

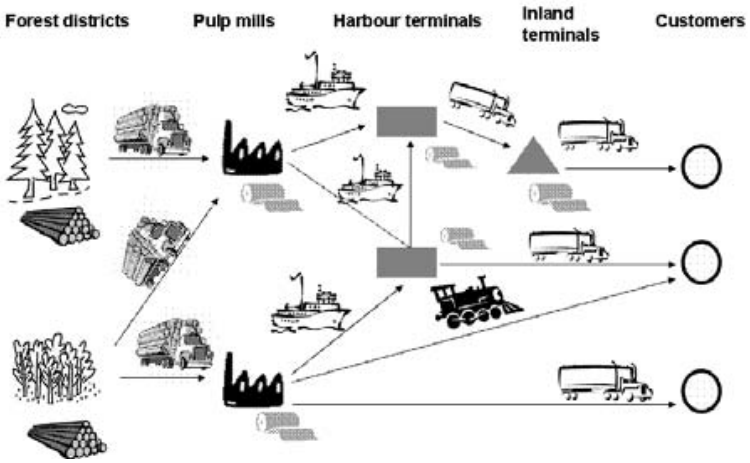

Figure 7: Illustration of the supply chain in Paper IV.

The focus in this paper is on the solution methods. Due to the large size of this problem, more advanced methods are needed to be able to solve the problem within reasonable time limits. The aim of this paper is therefore to develop a Lagrangian heuristic method based on Lagrangian decomposition for solving the mathematical model. The problem is decomposed into one subproblem per time period. In addition, two variants of a heuristic based on LP solutions, are developed. Cases including different numbers of variables and constraints are tested and evaluated. The number of binary variables included is 675–825 and the number of continuous variables is 370,811–3,489,036. The included number of constraints ranges from 71,289 to 274,217.

Paper V: Solving a multi-period supply chain problem for a pulp industry using Lagrangian heuristics based on physical stages

The problem in Paper V is the same as in Paper IV. A Lagrangian heuristic based on Lagrangian decomposition is used as well. The aim of this paper is to decompose the supply chain in another way compared to Paper IV, in order to improve solutions and solution times. The problem in this paper is decomposed into one subproblem per physical stage in the supply chain. In addition a heuristic based on division into physical stages are developed. Cases included different numbers of variables and constraints are tested and evaluated. The included number of binary variables is 675–825 and the number of continuous variables is 370,811–3,489,036. The included number of constraints is 71,289–274,217.

Contributions

My contribution to the research presented in this thesis includes major involvement in the modelling process and in writing the papers. I have developed and implemented the Lagrangian relaxation algorithms in the Papers IV and V as well as the heuristics in all of the papers. I have also taken part in the data collection. Mikael Rönnqvist and Jan Lundgren have participated in the work as my supervisor and co-supervisor, respectively. Dick Carlsson, industrial logistics manager at Södra Cell AB, complemented the work with the important industrial approach, mainly in Paper II and Paper III. Results from these papers are already used in practice by Södra Cell AB.

The papers have previously been presented by me at conferences in Budapest [28], Aspen [29], Åre [30], Växjö [37], Copenhagen [36], [34], Linköping [31], Molde [32], Reykjavik [33] and Pittsburgh [35]. Some of the papers have also been presented at internal seminars in the Optimization group in Linköping. Paper I and an earlier version of Paper II were presented at my licentiate seminar in February 2004 [26]. A condensed version of Papers IV and V will be presented at the EURO XXII conference on operational research in Prague in July 2007, [21]. Other related research not included in this thesis can be found in Gunnarsson et al. [27] and Karlsson et al. [41].

The main contributions of each paper are summarized below:

Paper I

- A new model describing the processes of handling forest fuel.
- Solution of the model using both a commercial solver and a new developed heuristic.
- Analyzing the model using real data.

Paper II

- A new model combining terminal location and ship routing.
- Solution of the model using a commercial solver and two new developed heuristics.
- Analyzing the model using real data.
- The result of the paper has been used in practice by Södra Cell AB

Paper III

- A new model describing the entire supply chain for a pulp company.
- Solution of the model using a commercial solver.
- Analyzing the model using real data.
- The result of the paper has been used in practice by Södra Cell AB.

Paper IV

- Development of a Lagrangian heuristic method based on time periods.
- Two variants of a rolling horizon heuristic are developed.
- Analyzing the solution method using real data.

Paper V

- Development of a Lagrangian heuristic method based on physical stages.
- A heuristic based on physical stages is developed.
- Analyzing the solution method using real data.

Suggestions for future research

New business models have been developed recently. One example is vendor managed inventory, VMI, which is used to a growing extent. The meaning of VMI, is that the distributor takes full responsibility for maintaining an agreed inventory of the products, usually at the buyerś location. Including this into the models, makes them even more large, and motivates developing of new solution methods to be able to solve them. That is a challenge and it is new change of getting better control and making larger profits for the involved companies.

The model for the supply chain concerning forest residues can be modified in order to be used for other kinds of biomass fuels. Since this study was completed in 2001, the prices of forest fuel used at heating plants have increased by almost 23% [67]. It is, therefore, more than ever motivated for suppliers of forest fuel to use the proposed model in order to be able to make the planning. An overall goal to use more bioenergy fuel together with the lack of forest fuel at some areas, also increase the interest of the presented model. Due to the higher prices on forest fuel, the pulp wood can in some ways work as a substitute for forest fuel. That can lead to strange situations and does of course impact the pulp market. The eventual conflicts between the energy sector and the forest industries are discussed in Lundmark [47]. He also tries to find out the break-point where it becomes more profitable to use round wood instead of forest residues as fuel. It could be interesting to include round wood in the presented model together with an increased demand. Then several scenarios could be tested in order to get more solution alternatives if the prices for forest fuel change dramatically. To create a mathematical model including the supply chains, or parts of the supply chains, for both forest fuel and pulp products would be a new and exciting challenge.

The models for the supply chain problems concerning pulp products presented in this thesis are complex and detailed, which motivates developing of more solutions methods in order to get good enough solutions faster. In addition to the Lagrangian heuristics method, other kinds of decomposition methods can be used, for example the Bender decomposition method. The convergence of the methods can probably be improved by adding and relaxing some aggregated constraints, especially in Paper IV. The constraints can also be scaled in order to make the values of the multipliers more alike. Another way to improve the solution times is to change the modelling language from AMPL for example to C.

Developing of decision support system, DSS, for the problems in the included

papers in this thesis, would enhance the possibilities for practical use of the presented models.

References

[1] R. Ahuja, T. Magnanti, and J. Orlin, Network Flows, (1993) Prentice Hall, New Jersey.

[2] A. Balakrishnan, J.E. Ward, and R.T. Wong, Integrated facility location and vehicle routing models: Recent work and future prospects, *American Journal of Mathematical and Management Sciences* 7 (1987) 35–61.

[3] D. Bertsimas and J. Tsitsiklis, Introduction to Linear Optimization, (1997) Athena Scientific, Belmont.

[4] J.H. Bookbinder and K.E. Reece, Vehicle routing considerations in distribution system design, *European Journal of Operational Research* 37 (1988) 204–213.

[5] D. Bredström, J.T. Lundgren, R. Rönnqvist, D. Carlsson, and A. Mason, Supply chain optimization in the pulp mill industry – IP models, column generation and novel constraint branches, *European Journal of Operational Research* 156(1) (2004) 2–22.

[6] A.M. Campbell and M.W.P. Savelsbergh, A decomposition approach for the inventory-routing problem, *Transportation Science* 38(4) (2004) 488–502.

[7] D. Carlsson, S. D'Amours, A. Martel and M. Rönnqvist, Decisions and methodology for planning the wood fibre flow in the forest supply chain, submitted to a CEMS book.

[8] D. Carlsson, S. D'Amours, A. Martel and M. Rönnqvist, Supply chain management in the pulp and paper industry, Working paper DT-2006-AM-3, Interuniversity Research Center on Enterprise Networks, Logistics and Transportation (CIRRELT), Université Laval, Québec, G1K 7P4, Canada, 2006.

[9] D. Carlsson and M. Rönnqvist, Wood flow problems in the Swedish forestry, The Forestry Research Institute of Sweden Report no. 1. (1999).

[10] Y.-C. Chang and C.-Y. Lee, Logistics scheduling: Analysis of two-stage problems, *Journal of Systems Science and Systems Engineering* 12(4) (2003) 385–407.

[11] M. Christiansen and B. Nygreen, A method for solving ship routing problems with inventory constraints, *Annals of Operations Research* 81 (1998) 357–378.

[12] M. Christiansen and B. Nygreen, Modelling path flows for a combined ship routing and inventory management problem, *Annals of Operations Research* 82 (1998) 391–412.

[13] M. Christiansen, Decomposition of a combined inventory and time constrained ship routing problem, *Transportation Science* 33(1) (1999).

[14] J.F. Cordeau, F. Pasin, and M.M. Solomon, An integrated model for logistics network design, *Annals of Operations Research* 144(1) (2006) 59–82.

[15] M.S. Daskin, C.R. Coullard, and Z.-J.M. Shen, An inventory-location mode: Formulation, solution algorithm and computational results, *Annals of Operational Research* 110 (2002) 83–106.

[16] M.S. Daskin, L.V. Snyder, and R.T. Berger, Facility location in supply chain design. In: A. Langevin and D. Riopel (Eds.), Logistics systems: Design and Optimization, (2005) Springer, 39–65.

[17] C. Dhaenens-Flipo and G. Finke, An integrated model for an industrial production-distribution problem, *IIE Transactions* 33 (2001) 705–715.

[18] K. Dogan and M. Goetschalckx, A primal decomposition method for the integrated design of multi-period production-distribution systems, *IIE Transactions* 31 (1999) 1027–1036.

[19] R. Epstein, E. Nieto, A. Weintraub, P. Chevalier, and J. Gabarró, A system for the design of short term harvesting strategy, *European Journal of Operational Research* 119 (1999) 427–439.

[20] R. Epstein, R. Morales, J. Serón, and A. Weintraub, Use of OR systems in the Chilean forest industries, *Interfaces* 29(1) (1999) 7–29.

[21] http://euro2007.vse.cz/, retrieved March 22 (2007).

[22] M.L. Fisher, The Lagrangian relaxation method for solving integer programming problems, *Management Science* 27(1) (1981) 1–18.

[23] A.M. Geoffrion, Lagrangean relaxation for integer programming, *Mathematical Programming Study* 2 (1974) 82–114.

[24] M. Guignard and S. Kim, Lagrangean decomposition: a model yielding stronger Lagrangean bounds, *Mathematical Programming* 39 (1987) 215–228.

[25] E.A. Gunn and A.K. Rai, Modelling and decomposition for planning long-term forest harvesting in an integrated industry structure, *Canadian Journal of Forest Research* 17 (1987) 1507–1518.

[26] H. Gunnarsson, Optimization approaches to tactical planning problems in the forest industry, Licentiate thesis LiU-TEK-LIC-2003:70, Linköping Institute of Technology, Sweden (2004).

[27] H. Gunnarsson, J. Lundgren, and M. Rönnqvist, Optimering kan sänka produktionskostnaderna för skogsbränsle, The Forestry Research Institute of Sweden, (2001) Report no. 20 (in Swedish).

[28] H. Gunnarsson, J. Lundgren, and M. Rönnqvist, Transportation of fuel wood, *Abstracts of the EURO XVII: OR application I*, Budapest, Hungary (2000) 118.

[29] H. Gunnarsson, J.T. Lundgren and M. Rönnqvist, Supply chain modeling of forest fuel. In: G.J. Arthaud and T.M. Barrett (Eds.), *Systems Analysis in Forest Resources: Proceedings of the Eighth Symposium, held September 27–30, 2000, Snowmass Village, Colorado, U.S.A.*, Kluwer Academic Publishers, Norwell, U.S.A. (2003).

[30] H. Gunnarsson, J.T. Lundgren, and M. Rönnqvist, Supply chain modeling of forest fuel. In: M. Palmgren and M. Rönnqvist (Eds.), *Proceedings of the workshop: Logistik och optimering inom skogsindustrin: Workshop – Åre 11–14 mars 2001*, Department of Mathematics, Linköping Institute of Technology, LiTH-MAT-R-2001-16, Sweden (2001) 49–58.

[31] H. Gunnarsson, M. Rönnqvist, and D. Carlsson, Annual planning of the supply chain and ship routing problem in the pulp industry. In: H. Aronsson (Ed.), *Nofoma 2004 Book of abstracts*, Linköping, Sweden (2004).

[32] H. Gunnarsson, M. Rönnqvist, and D. Carlsson, Annual Planning of the supply chain in the pulp industry, *TraLog –Transportation and Logistics, Abstracts Book, Molde University College*, Molde, Norway, 25-27 August 2004.

[33] H. Gunnarsson, M. Rönnqvist, and D. Carlsson, Integrated production and distribution planning for Södra Cell AB, Abstract in Proceedings of the second meeting of the EURO working group on operational research (OR) in agriculture and forest management, *Journal of Agricultural Science*, 144 (2006) 467–472.

[34] H. Gunnarsson, M. Rönnqvist, and D. Carlsson, Integrated production and distribution planning of the supply chain for Södra Cell AB. In: J. Clausen, R.M. Jørgensen, N. Kohl, J. Larsen and O.B.G. Madsen, *Proceedings of the 1st Nordic Optimization Symposium*, Copenhagen, Denmark (2006).

[35] H. Gunnarsson, M. Rönnqvist, and D. Carlsson, Optimizing the supply chain for a pulp industry using decomposition schemes, *Abstracts of the Informs annual meeting 2006*, Pittsburgh, USA (2006).

[36] H. Gunnarsson, M. Rönnqvist, and D. Carlsson, Terminal location integrated with ship routing. In: *Abstracts of the 18th International Symposium on Mathematical Programming: Facility location problems*, Copenhagen, Denmark (2003) 54.

[37] H. Gunnarsson, M. Rönnqvist, and J. Lundgren, Optimization of transportation, storage and chipping of forest fuel, *Proceedings of the 2nd Forest Engineering Conference: Decision support system/tools*, Växjö, Sweden (2003) 74–82.

[38] V. Jayaraman and H. Pirkul, Planning and coordination of production and distribution facilities for multiple commodities, *European Journal of Operational Research* 133 (2001) 394–408.

[39] B. Jonsson, J. Jacobsson and H. Kallur, The forest management planning package: Theory and application, *Studia Forestalia Suecica* 189 (1993) 1–56.

[40] J. Karlsson, M. Rönnqvist, and J. Bergström, Short-term harvest planning including scheduling of harvest crews, *International Transactions in Operational Research* 10 (2003) 413–431.

[41] J. Karlsson, P. Flisberg, H. Gunnarsson, and M. Rönnqvist, Modelling of road investments, Department of Mathematics, Linköping Institute of Technology, LiTH-MAT-R-2002-13, Sweden (2002).

[42] C. Kilger and L. Schneeweiss, Computer Assembly, *Supply Chain Management and Advanced Planning*, H. Stadtler and C. Kilger (Eds.), Springer-Verlag, Berlin (2005) 389–406.

[43] A. Kleywegt, V.S. Nori, and M.W.P. Savelsbergh, The stochastic inventory routing problem with direct deliveries, *Transportation Science* 36(1) (2002) 94–118.

[44] A. Kleywegt, V.S. Nori, and M.W.P. Savelsbergh, Dynamic programming approximations for a stochastic inventory routing problem, *Transportation Science* 38(1) (2004) 42–70.

[45] D. Li and C. O'Brien, Integrated decision modelling of supply chain efficiency, *International Journal of Production Economics*, 59 (1999) 147–157.

[46] B. Lidén and M. Rönnqvist, CustOpt: A model for customer optimized timber in the wood chain, Department of Mathematics, Linköping Institute of Technology, LiTH-MAT-R-2000-15, Sweden (2000).

[47] R. Lundmark, Cost structure of and competition for forest-based biomass, *Scandinavian Journal of Forest Research* 21 (2006) 272–280.

[48] D.L. Martell, E.A. Gunn, and A. Weintraub, Forest management challenges for operational researchers, *European Journal of Operational Research* 104 (1998) 1–17.

[49] H. Min, V. Jayaraman, and R. Srivastava, Combined location-routing problems: a synthesis and future research directions, *European Journal of Operational Research* 108 (1998) 1–15.

[50] N.H. Moin and S. Salhi, Inventory routing problems: a logistical overview, *Journal of the Operational Research Society* (2006) 1–10.

[51] G. Nagy and S. Salhi, Location-routing: Issues, models and methods, *European Journal of Operational Research* 177 (2007) 649–672.

[52] J. Nelson, J.D. Brodie, and J. Sessions, Integrating short-term, area-based logging plans with long-term harvest schedules, *Forest Science* 37 (1) (1991) 101–122.

[53] M. Näsberg, K.O. Jörnsten, and P.A. Smeds, Variable Splitting–A new Lagrangean relaxation approach to some mathematical programming problems, Department of Mathematics, Linköping Institute of Technology, LiTH-MAT-R-85-04, Sweden (1985).

[54] W.J. O'Brien, K. London, and R. Vrijhoel, Construction supply chain modeling: A research review and interdisciplinary research agenda, *Proceedings IGLC*, (2002) Gramado, Brazil.

[55] J. Olhager and E. Selldin, Supply chain management survey of Swedish manufacturing firms, *International Journal of Production Economics* 89 (2004) 353–361.

[56] M. Palmgren, M. Rönnqvist, and P. Värbrand, A solution approach for log truck scheduling based on composite pricing and branch and bound, *International Transactions in Operational Research* 10 (2003) 433–447.

[57] Y.B. Park, An integrated approach for production and distribution planning in supply chain management, *International Journal of Production Research* 43(6) (2005) 1205–1224.

[58] A. Philpott and G. Everett, Supply chain optimisation in the paper industry, *Annals of Operations Research* 108 (2001) 225–237.

[59] J. Rantala, Optimizing the supply chain strategy of a multi-unit Finnish nursery company, *Silva Fennica* 38(2) (2004) 203–215.

[60] R.L. Rardin, *Optimization in operations research*, Prentice-Hall, New Jersey (1998).

[61] M.P. Reinders, Tactical planning for a cutting stock system, *Journal of Operational Research Society* 44(7) (1993) 645–657.

[62] E.W. Richards and E. Gunn, A model and tabu search method to optimize stand harvest and road construction schedules, *Forest Science* 46(2) (2000) 188–203.

[63] E.W. Richards and E. Gunn, Tabu search design for difficult forest management optimization problems, *Canadian Journal of Forest Research* 33 (2003) 1126–1133.

[64] M. Rönnqvist, Optimization in forestry, *Mathematical Programming*, Series B 97(1-2) (2003) 267–284.

[65] M. Rönnqvist and D. Ryan, Solving truck despatch problems in real time, in *Proceedings of the 31th Annual Conference of the Operational Research Society of New Zealand*, August 31–September 1, Wellington, New Zealand (1995) 165–172.

[66] A.M. Sarmiento and R. Nagi, A review of integrated analysis of production–distribution systems, *IIE Transactions* 31 (1999) 1061–1074.

[67] *SCB: Statistical Yearbook of Forestry 2006, Official Statistics of Sweden*, National Board of Forestry, Jönköping (2006).

[68] Ş. Selçuk Erengüç, N.C. Simpson, and A.J. Vakharia, Integrated production/distribution planning in supply chains: An invited review, *European Journal of Operational Research* 115 (1999) 219–236.

[69] J.F. Shapiro, *Modeling the Supply Chain*, Duxbury (2001).

[70] Z.-J.M. Shen, Integrated supply chain design models: A survey and future research directions, *Journal of Industrial and Management Optimization* 3 (1) (2007) 1–27.

[71] Z.-J.M. Shen, C. Coullard, and M.S. Daskin, A joint location-inventory model, *Transportation Science* 37 (1) (2003) 40–55.

[72] http://www.sodra.com, retrieved April 20 (2007).

[73] H. Stadtler, Supply chain management and advanced planning–basics, overview and challenges, *European Journal of Operational Research* 163 (2005) 575–588.

[74] H. Stadtler and C. Kilger (Eds.), *Supply Chain Management and Advanced Planning*, Springer-Verlag, Berlin (2005).

[75] C. Todoroki and M. Rönnqvist, Dynamic control of timber production at a saw mill with log sawing optimization, *Scandinavian Journal of Forest Research* 17 (1) (2002) 79–89.

[76] C. Todoroki and M. Rönnqvist, Log sawing optimization directed by market demands, *The New Zealand Journal of Forestry* February (2001) 29–33.

[77] M. Wagner and H. Meyr, Food and beverages, in H. Stadtler and C. Kilger (Eds.), *Supply Chain Management and Advanced Planning*, Springer-Verlag, Berlin (2005) 371–388.

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

[79] A. Weintraub and R. Epstein, The supply chain in the forest industry: Models and linkages. In J. Geunes, P.M. Pardalos, and H.E. Romeijn (Eds.), Supply chain management: Models, applications, and research directions, (2002), Kluwer, Dordrecht, 343–362.

[80] A. Weintraub and C. Romero, Operations research models and the management of agricultural and forestry resources: A review and comparison, *Interfaces* 36(5) (2006) 446–457.

[81] L. Wolsey, Integer programming, (1998), John Wiley & Sons, New York.