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Supply Chain Planning of the Forest Product Industry using Operations Research

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Abstract. Over the years, operational research has been extensively used to support the Forest Product Industry and the Forest Public Organization in their respective planning activities concerning the fiber flow, from the forest to the customer. The applications range from long term strategic problems related either to forest management or enterprise development down to very short term operational problems such as real-time log/chips transportation planning or cutting problems. This paper presents an overview of the different planning problems and a review of the past contributions to the field. The focus is on applications and problem description.

Keywords. Forest management, harvesting, transportation, routing, supply chain management, forest product industry, production and distribution planning.

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1. Introduction

Supply chain planning has contributed to improve the performance of many companies. However, the challenge of integrating the different planning problems still remains. This is the case when procurement, production, distribution and sales activities need to be synchronized through a set of independent business units, suppliers and customers (e.g. entrepreneurs, carriers, sawmills, pulp and paper mills). The forest product supply chains are generally composed of many business units which are linked together and constrained by their various divergent processes. This is the case when, a mix of species grows in the forest, trees are cut into logs, logs are cut into boards or dimension parts and finally when paper reels are cut into smaller product rolls or sheets. Therefore, these many-to-many processes raises the complexity of integrating the procurement, production, distribution and sales activities as they are always bounded by tradeoffs between yield, logistics costs and service level.

Integrating the strategic, tactical and operational decisions is also critical in supply chain planning. Because of the size of the problems (e.g. number of products, processes, customers, suppliers and time periods), decomposition technique or hierarchical planning approaches are typically needed. Strategic decisions are constraining the tactical planning process and the tactical decisions are constraining the operational planning process. In the forest products industry, this is particularly challenging as the planning processes can span to more than 100 years, when dealing with forest management and down to fractions of a second, when dealing with operational cutting decisions.

Today, we find in the literature some review papers addressing different perspectives of the forest products supply chain. Rönnqvist (2003), Martell et al. (1998) and Epstein et al. (1999) reviewed the contribution of operation research to forestry, focusing on issues related to forest management, harvesting and transportation to wood consuming industries. More recently, Carlsson et al. (2006 and 2007a) completed these reviews by discussing the planning and distribution of the forest products such as paper, lumber, engineered wood product and biofuel. Weintraub and Romero (2006) include discussions about environmental and implementation issues.

From a global perspective, forest management and forest operations have great and direct impacts on the performance of the different supply chains using the wood fibre. This has been observed and reported many times by researchers involved in optimizing the forest decisions such as silviculture treatments, harvesting area and schedule, road construction in the forest, wood allocation and transportation. The Handbook on Operation Research in Natural Resource (Weintraub et al. 2007) presents in that regards many models aiming to improve the integrated planning of the forest and the enterprises, especially in a context of private forest owners.

The literature in the area is split in two parts. On one side, contributions to the forestry and more specifically to forest management, harvesting and transportation can be found and on the other side, contributions to the different products/markets based supply chain planning such as the pulp and paper, the lumber and engineered wood products and the biofuel can be found. The aim of this paper is to present an overview of theses contributions but also support the development of models which could better integrate the forest supply chain to the other forest products supply chains. This paper does not aim to cover exhaustively the literature but rather aim to point out key examples of forest planning problems.

The paper is organized as follows. In the second section, the fiber flow is explained from the forest up to the market. The main production processes and approaches are also discussed. The third section of the paper, reviews supply chain strategic, tactical and operational planning decisions for the forest products industry and explains them in general terms. Section four covers the literature reviews for the forest; pulp and paper, lumber and engineered wood and energy supply chains. As collaboration appears to be an important aspect of supply chain, recent papers addressing the challenge of collaboration and benefit/lost sharing are presented in section five. Finally concluding remarks are provided.

2. Fiber Flow

The flow of the many different products in the wood fiber supply chain is showed in Figure 1. The forest products supply chains can be viewed as large networks of production units which gradually transform the fiber into consumer products. In the different supply chains, the production network is linked to a procurement network which starts in the forest. The production network is also linked to a distribution network ending at merchants or retailers, which together with the end users, constitutes the sales network. Different transportation modes (e.g. trucks, trains and vessels) are used to transport the products from one stage to the other.

The forest products are transformed and distributed as they flow in the supply chain. The transformation activities involve generic “many-to-many” processes. These divergent processes consume a set of input products which are combined in different ways (e.g. recipes in the pulp and paper industry) or cut following different cutting patterns (e.g. bucking or sawing patterns) to produce a set of output products. These outputs are classified into co-products and by-products. The co-products are all demand-driven products whereas the by-products are generated by the process and need to be sold on side markets. The by-products are usually low value products such as bark or saw dust.

In many circumstances, the transformation can be conducted following alternative processes (e.g. recipes or cutting patterns). When dealing with these alternative processes, the planning decisions must also select the processes to be conducted.

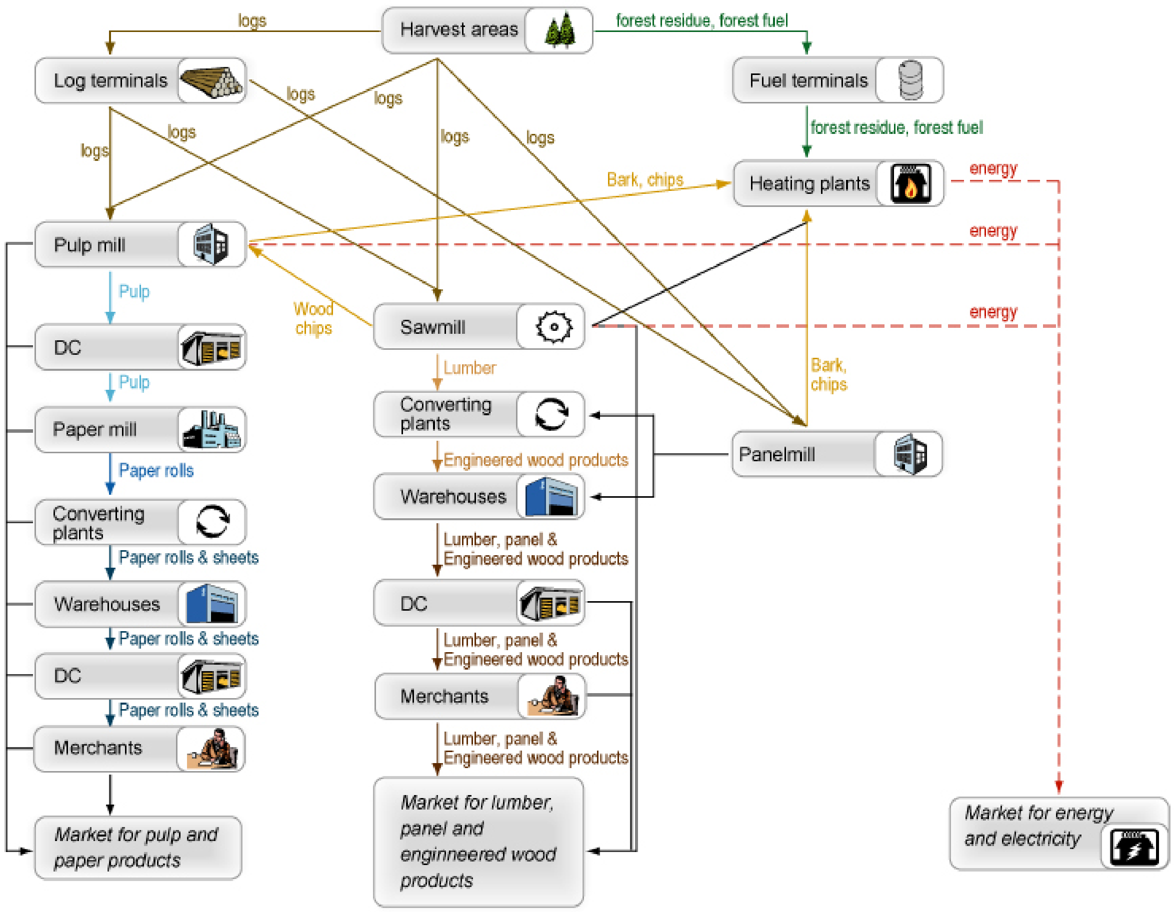

Figure 1 : The different supply chains of the forest products industry

The different enterprises of the wood product industry typically own a set of business units involved in the transformation and distribution of the forest products. When an enterprise spans from the forest to the distribution network, it is said to be integrated. Moreover, some large and global enterprises are active in all the different markets showed in figure 1. This is the case for example of Stora Enso, a global corporation, with its head office in Finland. This enterprise is by itself composed of many interrelated supply chains.

The forest supply chain is challenged by the task of producing trees for different usages. The processes include strategic forest management issues such as land management and silviculture treatments down to operational issues related to harvesting and transportation. Planning the forest supply chain involves dealing with a very long planning horizon, anticipating natural disruptions like fires, considering multiple societal needs and meeting industrial demands. Depending on the nature of the forest (e.g. species, age, soil and plantation) and the tenure mode, the planning problems may differ between countries and regions. However, one common objective still remains; that is the need for higher integration between the forest supply chain and the industrial supply chains (pulp and paper, lumber and engineered wood, energy). The harvesting consists of the following major stages. The trees are cut and branches are removed. Thereafter the tree is bucked (or cross-cut) into logs (with specific dimensions and quality). This process can either be done at the harvest areas or in wood yards. Trees or logs are transported from harvest areas directly to mills or through intermediate storage at terminals. The harvesting is done by a set of harvest crews and the transportation by one or several transport companies. The overall harvest and transportation planning are often integrated.

The pulp and papers supply chains transform logs or chips into pulp, then paper and convert the paper into commercial rolls or sheets. The distribution network often involves many echelons as the pulp and paper products can be solved directly to paper mills, printers or large retailers or through a network of merchants and wholesalers. In pulp production, the fibers are mixed with chemicals following a specific recipe to produce the pulp grades. Recycled paper is often introduced in the production of the pulp products. The pulp is then used to produce jumbo reels of paper of a specific grade, finish, base weight and colour. The jumbo reels are cut into rolls which can be either sold on the market and or sheeted into printing and writing paper products. From the mills, the paper is distributed either directly or through a network of wholesalers, merchants and distributors. Customer varies depending of the type of papers (e.g. news print, fine paper and packaging), they can be for example, printers, retailers or food chains. A typical company in the pulp and paper industry would own many mills. All transportation modes are used in this supply chain. Between the forest and the mill, trucks, trains and vessel transport the logs or chips to the pulp mills. The pulp products are transported by all modes but a majority is by vessels or trains. The finished paper is normally transported by train or truck.

The lumber, panel and engineered wood industry transform the logs into boards to produce lumber and dimension parts or flakes to produce panels. The boards and the panels are used as components for engineered wood products. The wood products are mainly used for building or appearance usage.

Lumber is produced in stages. First there is a breakdown of logs into boards in sawmills. Second, boards are dried in dry kilns and last, they are planed in finishing lines. In modern North American sawmills, scanners read the geometry of the logs and optimize the cutting in order to produce maximum value. To prevent production bottlenecks, a mix of logs is used in the sawing lines. Drying can be both a batch and a continuous process. The boards are grouped following specific configurations in order to maximize the quality of the outputs. Finally, the finishing process is conducted on a line where setups are constraining the process. The setup times are mainly due to the emptying of the buckets containing the finished products.

Panels are produced from wood flakes which are dried, glued and pressed together. The flakes are produced from logs that have been stored in ponds to be softened. The flakes are spread on a mattress and are then cut in length. The panels fill up slots of a large press. When the panels are used to make engineered wood products such as prefabricated wood I-beams they are cut again to fit specifications.

Engineered wood products are typically produced through an assembly of lumber and panels. They are used for structural parts in residential and non-residential constructions (for example flooring or roofing systems). Many standards regulate the lumber, panel and engineered wood products. For example, in North America, softwood lumber is conforming to the NLGA (National Lumber Grade Authority) certification defining grading rules for softwood lumber of certain dimensions while the hardwood lumber is conforming to the NHLA (National Hardwood Lumber Association) grading rules.

Customers show different buying behaviors which are all strongly affected by the variation of the spot market prices. These behaviors can be classified in three different categories: spot market, vendor managed inventory and contract based. The vendor managed inventory and contract based approaches usually provides a financial advantage to the producer in exchange for committed deliveries.

The energy industry uses the forest residues to produce energy. The forest biomass is supplied either directly from the forest or from the mills. The biomass serves as biofuel to produce the energy. It can be transported bulk, bundled or chipped. The chipping can be done in the forest, at the terminals or at the heating plants. Some chemical processes can transform the residues into specific biofuel such as the ethanol. The supplied energy aims to satisfy public needs (e.g. heating plants that support residential and industrial areas with hot water for heating) or industrial needs (e.g. drying kilns). As the cost of fuel is rising, the opportunity of using wood residues for energy becomes more interesting.

3. Supply Chain Planning in the Forest Product Industry

Supply chain planning in the forest product industry spans from strategic decisions down to operational decisions. The next subsections stress the scope of these decisions and the specific issues of the Forest Product Industry. Finally, as an example, Table 1 states the specific strategic, tactical and operational planning decisions to be taken in a pulp and paper supply chain.

3.1. Strategic planning

Long-term planning in the forest products industry is indeed very long-term. The rotation of some forest growth can span over more than 80 years. An investment in a new pulp or paper mill is normally intended to last for more than 30 years. Strategic decisions include forest management strategy, silviculture treatment, conservation areas, road construction, opening and closing of mills, location of new mills or to be acquired mills, process investment (e.g. machine, transportation equipment, information technology), products and markets development, financial and operational exposure, planning strategy (e.g. make-to-stock, make-to-order, cut-to-order) and inventory location (e.g. location of the decoupling point and of the warehouses).

Defining the planning approach has a major impact on all the investment decisions. The capacity needs and the type of equipment needed to support a make-to-stock strategy versus a make-to-order strategy would typically be different. Therefore, the planning strategy fixes important parameters in terms of needed technology and capacity as well as inventory levels and maximum distance to customers. Such decisions involve naturally an evaluation of how the investment will fit into the whole supply chain. Which markets are available for the products based on anticipated market trends? How will the distribution of the products be carried out and at what cost? And finally how should the production be supplied with the necessary wood fibers (wood or pulp)? Other supplies such as energy might also be a crucial factor.

The forest tenure mode may affect the way strategic decisions are made in the supply chain. Wood would come either from crown lands, private lands or both, imposing different procurement programs. Other aspects are also important. One example are governmental rules to increase the area of the forest areas set aside for bio-diversity, recreational use and carbon sequestration.

Although the literature provides a broad and rich understanding of strategic supply chain planning and proposes different solving methodologies, very few contributions can deal with divergent and alternative production processes as well as with mixed demand behaviors (spot and contract based demand) which raises the need for specific methodological contributions. Moreover, very few contributions where applied to the forest products industry raising the need for industry implementation knowledge and most of all, for the integration of the decisions related to forest management and forest operations to the other downstream supply chain planning decisions.

3.2. Tactical planning

The next step in the hierarchical planning structure is mid-term or tactical planning. The meaning of tactical planning is slightly different if one is addressing a forest management problem or a production/distribution planning problem. In forest management, hierarchical planning approaches are widely used as they permit to first address the strategic planning problem without taking into account spatial issues. The tactical planning is then tightly spatially constrained. The decomposition is needed here mainly to content the size of each problem. If the strategic forest management planning problem generally spans over 100 years, the tactical planning problem is often viewed as annual planning over a five year planning period.

From the production/distribution point of view, tactical planning typically addresses allocation rules which define which resource or group of resources should be responsible for realizing the different supply chain activities. It also addresses the usage rules defining production, distribution delays, lot sizing and inventory policies. An important contribution of the tactical planning is to define those rules through a global analysis of the supply chain. This planning serves as a bridge from the long-term strategic level to the detailed operative planning which has a direct influence on the actual operations in the chain (e.g. routing of trucks, definition of when to change from one product to another in the production process etc.). The tactical planning should ensure that the subsequent operative planning follows the direction which has been set out in the strategic planning even though the planning horizon is shorter. Other typical tactical decisions are allocation of customers to mills and definition of necessary distribution capacity. The requirement of advance planning of the distribution depends on the transportation mode. Typically vessel, and rail transportation needs to be planned further in advance than trucks.

An important reason for tactical planning is the need for advance planning if there is seasonality in the supply chain. Seasonality influences greatly on the procurement stage (i.e. the outbound flow from the forests). One reason is shifting weather conditions over the year which may make it impossible to carry out transportation during certain periods because of lack of carrying capacity on the forest roads due to thaw. In many areas of the world, there is also seasonality prevailing in the harvesting operations. In the Nordic countries, for example, relatively a small proportion of the annual harvesting is done during the summer period (July-August). During this period operations are focused on silvicultural management such as regeneration, cleanings, etc. During the winter relatively a larger proportion is harvested. This is when the ground is frozen and there is less risk of damages during forwarding operations of the logs out of the forest. Seasonality can also affect the production stage, as for example in the Nordic countries, drying time of hardwood can vary over the season. It can also affect the demand process, as again, for example in the Nordic countries, most of the construction projects would be conducted during the warm seasons.

In most companies, an important task is the annual budgeting of the following year. During this planning exercise, the company decides which products to offer to customers and in what quantities. In the process of elaborating these decisions, their implications on the whole supply chain (procurement, production and distribution) needs to be evaluated and net profit maximization should be the aim. In that regard, Shapiro (2001) suggests that the tactical planning models be derived from the strategic planning models where the 0-1 variables related to the strategic decisions are fixed and the planning horizon is extended to a multi-period (multi-seasonal) horizon. The solution can then provide insights supporting the budget definition for each of the business units within the supply chain.

3.3. Operative planning

The third level of planning is the short-term or operative planning, which is the planning that precedes and decides real-world operative actions. Because of that, this planning process needs to adequately reflect in detail the reality in which the operations take place. The precise timing of operations is crucial. It is normally not enough to know during which week or month a certain action should be taken, it has to be defined in terms of days or hours. The operative planning is normally distributed to the different facilities or cells of the facilities because of the enormous quantity of data that needs to be manipulated at that level (e.g. number of Stock Keeping Unites (SKU) and specific resources).

One operative problem is the cutting problem which is found in many of the wood product mills (e.g. lumber, dimension parts and pulp and paper).

Another large area of operative planning problems is within transportation. Routing and dispatching matters appear between several segments of the supply chain. Routing of the truck fleet used for haulage of wood from the forest to the mills is needed as well as routing of the trucks for the distribution of finished products from mills to customers or distribution centers.

Within the production process, scheduling of the different products on the manufacturing lines are also typical operational planning tasks. Finally, the process control involves real time operative planning decisions. The process control is particularly critical in the pulp and paper industry as the characteristics of the output products are highly sensitive to the precision of the mix of chemicals and fibers.

Table 1 presents a review of the strategic, tactical and operative planning decisions for the pulp and paper industry. The supply chain planning matrix was proposed by Carlsson et al. (2006). This proposal followed a series of case studies conducted in the Swedish pulp producer Södra Cell (Carlsonn et al. 2005).

	Procurement	Production	Distribution	Sales
Strategic	• Wood procurement strategy (private vs public land) • Forest land acquisitions and harvesting contracts • Silvicultural regime and regeneration strategies • Harvesting and transportation technology and capacity investment • Transportation strategy and investment (e.g. roads construction, trucks, wagons, terminal, vessels, etc.)	• Location decisions • Outsourcing decisions • Technology and capacity investments • Product family allocation to facilities • Order penetration point strategy • Investment in information technology and planning systems (e.g. advance planning and scheduling	• Warehouse location • Allocation of markets/customers to warehouse • Investment in logistics resources (e.g. warehouse, handling technologies, vessels) • Contracts with logistics providers • Investment in information technology and planning systems (e.g. warehouse execution	• Selection of markets (e.g. location, segment) – customer segmentation • Product-solution portfolio • Pricing strategy • Services strategy • Contracts • Investment in information technology and planning systems (e.g. On-line tracking system, CRM)
Tactical	• Sourcing plan (log class planning) • Harvesting aggregate planning • Route definition and transshipment yard location and planning • Allocation of harvesting and transportation equipment to cutting blocs and • Allocation of product/bloc to mills • Yard layout design • Log yard management policies	• Campaigns duration • Product sequencing in campaign • Lot-sizing • Outsourcing planning (e.g. external converting) • Seasonal inventory target • Parent roll assortment optimization • Temporary mill shutdowns	• Warehouse management policies (e.g. dock management) • Seasonal inventory target at DCs • Routing (Vessel, train and truck) • 3PL contracts	• Aggregate demand planning per segment • Customer contracts • Demand forecasting, safety stocks • Available to promise aggregate need and planning • Available to promise allocation rules (including rationing rules and substitution rules) • Allocation of product and customer to mills and distribution centers
Operational	• Detailed log supply planning • Forest to mills daily carrier selection and routing	• Pulp mills/paper machines/winders/ sheeters daily production plans • Mills to converters/DCs/ customers daily carrier selection and routing • Roll-cutting • Process control	• Warehouses/DCs inventory management. • DCs to customer daily carrier selection and routing • Vehicle loads	• Available to promise consumption • Rationing • Online ordering • Customer inventory management and replenishment

Table 1. Supply chain planning matrix for the pulp and paper industry (Carlsson et al. (2006))

3.4. Methodology

A full range of OR methodologies are used to support the planning problems of the forest product industry. Rönnqvist (2003) presents typical planning problems on would find the forest product industry. The author also comments on the available time to solve each of these typical problems. Operational problems typically need to be solved rapidly, within seconds or minutes, while long term strategic planning problem can take longer time, up to many hours, to be solved. Therefore, heuristics, meta-heuristics and easy to solve network approaches are typically used for operational problems while Mixed Integer Programming (MIP) and stochastic programming methods serve better the tactical and strategic planning problems. Many of the OR models are implemented in different industrial Decision Support Systems (DSS). Often these DSS are integrated with application specific databases holding all the information needed for the models and Geographical Information Systems (GIS) for visualizing the input data and results.

4. Literature review

4.1. Forest management and harvest operations

Forest management

The forest supply chain is for sure one of the very strategic part of the three main products supply chain described in this paper. An important characteristic is that the different business units are typically highly geographically distributed as they are dealing with different operations, e.g. planting, thinning, road construction, harvesting, storage and transportation. The forest supply chain needs to solve the allocation problem of wood to different usages. For the economical usage, the problem is then to distribute the wood to the different supply chains. The decisions span from strategic decisions down to operational decisions. The strategic decisions are long term aiming to attain societal targets defined in order to meet socio-economical sustainable development. Some of these strategies span over several rotations which means for some countries planning for more than 100 years. They have great impact over time on the quality and volume of the available fiber.

Strategic forest management puts the emphasis on the link between decisions related to forest usage, such as harvesting areas, allocations, silviculture treatments, and to their different socio-economical issues such as environmental issues, non declining yield, employment, access to the forest and industrial competitiveness. To support managers and forest public organizations in their decision making, numerous models have been developed. Some of these models build on operational research (e.g. harvesting planning, road construction and maintenance planning), while others builds on simulation (e.g. growth simulation, ecological impact). Finally, economical models serve to link fiber availability to the value of the forest products (Gunn, 2007). In a context of crown land, establishment of the forest regimes is a governmental exercise. Typically, the governments rely on simulation to evaluate the impact of different forest management strategies as they need to take into account multiple criteria in their decision makings (Davis et al., 2001).

The 70's and the 80's have been flourishing in terms of linear programming models such as the FORPLAN use by the USDA Forest Service. These models take into account information on growth, biodiversity and requirements in terms of protected areas and spatial requirements. Forest management strategies are treated in such models as constraints (Gunn, 2007) while the spatial constraints are not yet considered. In these models, one would normally found a non-declining yield set of constraints.

Once the forest management strategy is established, the tactical and operational planning decisions are taken in an integrated way with the need of the different supply chains. The harvesting areas are defined precisely as well as the transportation infrastructure, all subjected to the constraints of the strategic plan and the spatial constraints. Recent simulation models permit to represent the growth of each block as well as their spatial location (Bettinger and Lenette, 2004). Therefore, multiple plans can be evaluated considering the spatial issues.

Allocation of fiber to producer is a universal problem. In countries where the forest is characterized by a private ownership, the flexibility seems to be higher as allocation decisions can be taken simultaneously to transportation decisions.

However, considering all the possibilities and the enormous quantity of information required to manage when planning the forest operations, many favors hierarchical planning approach. In the first step, the treatment are decided in terms of volume and in the second step, these decisions become constraints to spatial planning (Weintraub and Cholasky, 1991; Hof and Pickens, 1987; Church et al. 1994).

Spatial and environmental concerns

With the advent of GIS and associated spatial data, there is an increasing concern for spatial relationships and environmental conditions present in integrated forest management and harvest planning. Particular issues of interest include wildlife richness, creating habitat that is favorable to flora and fauna, fomenting diversity, ensure soil and water quality, preservation of scenic beauty and sustainability. These issues are addressed in tactical models either implicitly or explicitly by structuring necessary constraining relationships and limiting spatial impacts.

One of the primary ways that spatial relationships and environmental conditions have been modeled at the tactical level is through the use of adjacency restrictions with green-up requirements. In particular, a maximum local impact area limit is established to restrict local activity for a specified duration of time. For the case of clear cutting, this corresponds to a maximum open area that is imposed on any management plan. An important wildlife requirement is maintaining mature habitat patches which are contiguous areas of a certain age where animal can breed and live. To ensure this, potential areas are to be grouped to form patches (Öhman and Eriksson, 1998).

A number of models include the maximum opening area and adjacency constraints and they can be grouped into two approaches. These are called unit restriction models and area restriction models. In the first approach, harvest areas are constructed in such a way that if two adjacent areas are cut they would violate the maximum opening restriction (Murray 1999). In the second approach, the harvest areas are not predetermined and are generated using smaller building blocks. With this model it is possible to harvest adjacent areas but restrictions on maximum opening areas must be dealt with directly in the formulation. The second approach has a clear advantage as many more possibilities can be included (McDill et al. 2002; Murray and Weintraub 2002; Goycoolea et al. 2003).

Although strategic forest management decisions are supported by timber supply models, they typically lack in there ability to integrate the transformation capacity of the forest owner or its customers (located capacity and technology) and the value and cost of forest products which are tightly linked to the location of the transformation capacities and the markets. Gunn and Rai (1987) raise this issue and propose a model supporting long-term forest harvesting planning in an integrated industry structure.

Tactical harvesting and transportation

The tactical level of planning in forest management is typically associated with making decisions on how to treat standing timber over a horizon of several years to decades. Historically decision variables in tactical models related to the selection and sequencing of stands or cutting blocks for harvesting in order to satisfy temporal timber demands. In addition, road engineering is a necessary component of tactical planning as the industry is dependent on an efficient road network. The reason for this is that roads provide access to harvest areas and associated costs impact management plan viability. Thus, tactical planning is supported by the use of mixed integer linear programming in order to model decisions on where and when to harvest as well as which roads to build (or maintain).

One of the classic works in road building is that of Kirby et al. (1986), which saw significant use by the US Forest Service. Questions related to the deployment of the forest road system and to the selection of the transportation infrastructure are strategic decisions leading to MIP problems (Epstein et al., 2007b). Richards and Gunn (2000) explain well the challenges related to the design of network. Andalaft et al. (2003) present a model called OPTIMED. The model aims to optimize simultaneously the harvesting plan and the deployment of the road network over a 2 to 3 years planning horizon. Olsson (2004) and Henningsson et al. (2007) present a MIP model which includes decisions concerning restorations of existing forest roads and transportation. The problem is to provide available harvest areas during the thawing part of the year when only some roads are accessible. The models are used as a basis for a decision support system RoadOpt (Frisk et al, 2006a) developed by the Forestry Research Institute of Sweden.

Transportation is a major part of forest operations. It can constitute up to 40% of the operational costs. In some cases, the harvest planning is combined with transportation and road maintenance, on an annual planning horizon. A MIP model to solve this problem is proposed in Karlsson et al. (2004). In Karlsson et al. (2003) a model integrating handling of crews, transportation and storage is described. Other important issues in transportation include the possibility of integration of trucks with there transportation modes, specifically, ship and train are included (Forsberg et al., 2005; Broman et al., 2006). Finally, transportation operations are the operational link between the forest's supply chain to the other supply chains. Considering that the transportation costs account for a high proportion of the total fiber cost to mill, many teams around the world have worked on these problems in order to reduce the costs through optimal backhauling (Carlsson and Rönnqvist, 2007).

Most models developed so far to support forest planning does not take into account market or prices. It is only at the operational levels that these factors are considered, as it has been in Beaudoin et al. (2007a). In their proposal, the blocks to harvest are decided considering the demand plan of the mills and the volume constraints from the forest. Freshness is also considered as it impacts on production and inventory costs. Transportation costs are taken into account in the model. The harvesting plan obtained maximizes profits by increasing revenues with an efficient allocation of wood to mills and by reducing operating and transportation costs. Prices are set as a function of supply volume and freshness.

Operational harvesting

Forest operations correspond to the actions taken which directly affect harvest operations (Epstein et al. 2007a). In flat areas, skidders are used to bring logs to roadside. Secondary roads need to be built to reach towers or reduce distances traveled by skidders, to load logs into trucks. GIS systems have been used to develop computational tools to better plan the decisions on location of machines and roads. PLANS (Twito et al. 1987) was an early system developed by the US Forest Service and a similar system was introduced in New Zealand (Cossens, 1992). Both act as simulators. The user proposes the machine locations and the system determines in a visual interactive way the areas to be harvested by each machine, the roads to be built and the timber volumes harvested. Jarmer and Sessions (1992) developed a system to analyze the feasibility of cable logging configurations. Epstein et al. (2006) developed a system that incorporated the decisions on machine location. The system was used successfully by forest firms in Chile and Colombia. It is based on an interaction with a GIS, and a heuristic to determine good solutions. Flisberg and Rönnqvist (2007) describe a system to support forwarding at harvest areas. By using a DSS the forwarding operations can be improved about 10% through better routing. In addition better information on supply location and volumes can be gained for later truck transportation planning.

Products are defined typically by length and diameter of the logs, and also by quality. The lower part of the tree, of higher diameter has a higher value and is sent to high end sawmills. The upper, thinnest part of lesser value is best suited for pulp and paper mills. It is not easy to match exactly the available standing timber with specific order of products. LP models have been particularly useful in this regard, reducing significantly the loss incurred when higher diameter logs are used for lower value purposes such as pulp.

Carlgren et al. (2006) develop a MIP model that integrates sorting at harvest areas and transportation. Sorting of assortments in the forest will lead to higher harvest and transportation cost but also provide better quality logs for production at saw mills. By using backhauling the effect of increased harvest cost can be reduced through improved transportation planning.

In many cases bucking decisions are integrated into the decisions on stands to harvest. The number of possible bucking patterns is very high, given the many combinations of lengths and diameters. Different methodologies were explored by McGuigan (1984); Eng et al. (1986); Mendoza and Bore (1986); Briggs (1989) and Sessions et al. (1989). Successful applications were reported by use in New Zealand (Garcia 1990) and in Chile (Epstein et al. 1999).

Bucking can also be carried out at the processing plants, where each tree can be scanned and analyzed individually or by implementing optimizers into mechanical harvesting at forests. Two basic approaches have been considered (Marshall, 2007). Buck-to-Value, where specific prices are assigned to each product, and Buck-to-Order, where products are determined based on specific orders to be satisfied. Dynamic Programming and meta-heuristics are main algorithms proposed. Commercial codes have been developed and are used by forest firms.

Operational routing

An early DSS for logging trucks is ASICAM (Weintraub et al. 1996) which is used by several forest companies in Chile and other South American countries. It produces a schedule for one day by a simulation based heuristic. The Swedish system RuttOpt (Flisberg et al. 2007; Andersson et al. 2007) establish detailed routes for several days and integrates GIS with a road database, and uses a combination tabu search and an LP model. Tests carried out report costs reductions between 5% and 20% compared to manual solutions.

In Palmgren et al (2003, 2004) Branch & Price methods are used to solve a column (route) based formulation with a one day planning horizon and one truck type. The subproblem for finding routes was based on various heuristics. Murphy (2003) formulates a general integer programming model for the routing model, but uses it only for tactical long term planning. Gronalt and Hirsch (2005) describe a tabu search method where a set of fixed (destination) transports are to be performed. Time windows and multiple depots are included in the formulation. The problems studied are of small sizes and consider only one time period.

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

Other systems that are based on tactical flow models but used for manual route and scheduling are Åkarweb and MaxTour. Åkarweb (Eriksson and Rönnqvist, 2003) is a web based system that each day computes potential transport orders by solving an LP based backhauling problem. MaxTour (Gingras et al., 2007) is developed in Canada and establishes routes based on the classical heuristic by Clarke and Wright by combining predefined loads in origin-destination pairs. In this system the destination of logs is already determined and MaxTour is mainly used to establish single backhauling routes and not schedules.

Fire

In this subsection, fire is addressed as one example of the natural disruption that occurs in Forest and therefore affects the supply chain planning.

Fire management spans from long term integrated planning of fire and forest management to short term dispatching of fire crews to stop fire expansion. The scope of fire management can vary between countries du to their difference in climate, vegetation and societal needs (Martell 2007). Martell (1982) and Martell et al. (1998) present literature reviews on the subject. As the impact of fire can be very important either in terms of forest management or in terms of supply chain planning it requires some consideration.

As stated by Martell (2007), forest fire management could be defined as getting the right amount of fire to the right place, at the right time and at the right cost, raising the need to balance the beneficial and detrimental impacts of fire on people and forest ecosystems at a reasonable cost to society.

Fires are stochastic processes, which are either caused by people or lightning. This explains why significant effort has been dedicated to build good predicting models, anticipating the amount of fires to occur over time periods and space. For example, Cunningham and Martell (1973) studied daily people-caused fire occurrence and showed a Poisson distribution of the expected number of fires in a region per day. The expected value however varies with weather observations. As for lightning-caused fire, an example of such predicting models can be found in Kourtz and Todd (1992).

Fire prevention and detection are two important aspects of fire management. Some forest fire management agencies use fixed towers or lookouts to continuously check over some specific forest areas while some use detection patrol aircraft. The design of these systems rises interesting OR challenges. How many towers, where? How many patrol aircraft to charter, which type, when and where? For example, simulation has been used by Mees (1976) to evaluate potential towers location. While the Canadian Forest Service developed many strategic and tactical detection system models over the years to address the aircraft management issues (Kourtz, 1967; Kourtz, 1971; O'Regan et al., 1975).

Initial attack resource deployment and dispatching are the processes which are launched when a fire occurs. This problem is challenged by the fact that the fire arrival rates and service times may vary throughout the day calling for varying resource needs over the day. The specific initial attack dispatching problem was defined by Martell (2007) has the determination of what resources (e.g., fire fighters and airtankers) will be dispatched (by ground and/or air) to each fire that is reported, and when more than one fire is burning out of control, they must prioritize them and decide which will be attacked first or which will receive most of the scarce resources.

4.2. Pulp and paper

It is only recently that the issues of supply chain design in the pulp and paper industry attract the attention of practioneers as well as researchers. This can be partly explained by the fact that the industry was typically driven by a push based model where the main decisions were related to when and where to cut the trees. The next steps were processing and selling the resulting products. The following present recent specific contributions to the field.

One of the first to address production-distribution networks design in the pulp and paper industry was Benders et al. (1981). They explain how International Paper, the largest pulp and paper company in the world, analyzed and solved its network design problems with mathematical programming models.

Martel et al. (2005) present an OR model to optimize the structure of multinational pulp and paper production-distribution networks. The authors aim to identify the main international factors having an impact on the industry and show how they can be taken into account in the design of the supply chain. The discussed factors include national taxation, transfer price regulations, environmental restrictions, trade tariffs and exchange rates. Adding these features to the planning model, however, adds considerably to the complexity of the problem. Martel et al. (2005) suggest how this can be done based on a general production-distribution network model dealing with many-to-many processes. The proposed activity-based model is a large mixed integer program where fiber supply is considered as a constrained supply source.

Gunnarsson et al. (2007) develop a model for strategic planning of Södra Cells kraft pulp supply chain. The main purpose of the model is to optimize the allocation of the various products to mills. Södra Cell has five pulp mills, three in Sweden and two in Norway, producing kraft pulp. The whole pulp supply chain is described using a MIP model. On the demand side of the model all potential contracts with individual customers are defined together with the expected net prices to be achieved. The user can define whether a certain contract has to be taken to its full extent or if the model can choose to take it or not. Various different means of transportation can be selected to deliver the pulp to the final destination. Pulp recipes are allowed to vary within a min/max-range in terms of the share of different wood assortments used to make different products. The model is used by Södra Cell's management to evaluate different scenarios of wood availability and cost. Another typical use of the model is to optimize the composition of the product portfolio. A kraft pulp mill suffers very much from having to produce many different products, since transition costs are relatively high, especially when mixing hardwood and softwood on the same production line. Gunnarsson et al. (2006) deals with strategic design of the distribution network. Södra Cell operates three long term chartered vessels dedicated to the pulp distribution only. How well the routing of these vessels can be done depends on the terminal structure. With a few terminals each having a large volume turnover, there is a great chance that the vessels can be unloaded at one single terminal, whereas if many small terminals are used, the vessel probably has to pass two or several terminal to be unloaded. The authors develop a model in which terminal location is combined with vessel routing. This is an example of planning on a strategic level where it is important to account for some operative aspects, in this case the ship routing.

Philpott and Everett (2001) present the work carried out within Fletcher Challenge to develop a model (PIVOT) for optimization of the paper supply chain. PIVOT is used to optimally allocate suppliers to mills, products to paper machines, and paper machines to markets. The core of the model is a fairly generic supply chain model formulated as a mixed integer program. In addition a number of restrictions are added to model mill specific conditions such as interdependencies between paper machines in a mill, and distribution cost advantages in certain directions due to backhauling opportunities. The successful implementation of PIVOT led to further development of the model by the authors in cooperation with the management of Fletcher Challenge. In Everett et al. (2000) the SOCRATES model is described which was developed for planning investments on six paper machines at two mills located on Vancouver Island in Canada. The main features distinguishing SOCRATES from PIVOT is that capital constraints are introduced and that a multi-period planning horizon is used. A further development of the model was achieved in the COMPASS model (Everett et al. 2001), which was implemented for three Norske Skog mills in Australia and New Zealand. The objective function was modified to account for taxation in the two countries. The other main feature added was that the paper furnish was allowed to vary, in terms of different wood pulps used, depending on capital investment decisions. The intention was to evaluate possibilities to use a less costly furnish based on capital investments done on the paper machine.

A crucial part of the supply chain is the procurement of appropriate wood fibers for the different final products eventually being produced. For that purpose wood is sorted into different assortments with specific properties. Sorting into more assortments is however costly and is a decision that normally can not be taken independently by one single party. Weigel et al. (2005) present a model optimizing wood sourcing decisions including wood sorting strategies as well as technology investments decisions in order to maximize the profit of the supply chain. The objective of the model is to maximize the contribution margin of the supply chain, i.e. sales revenues minus various fixed and various costs. The model assumes that wood available in aggregated supplies can be sorted in different ways into distinct grades. Each pulp and paper product can be made according to a set of viable recipes involving the wood grades in different proportions. The authors show, using a test case, that substantial improvement in objective value can be achieved by optimally allocating fiber types to the right process stream and at the same time optimize the output of the supply chain into different end-products.

Interesting models were developed recently to support tactical planning in the pulp and paper industry. For example, one was developed for the Swedish pulp producer Södra Cell (Bredström et al., 2004). The model stretches from individual wood sources, to the mills down to aggregate demand zones. It produces individual production schedules for the mills. In comparison with manual planning, the optimized schedules reduce the global storage and logistics costs even though the number of changeover increases.

Bouchriha et al. (2005) develop a model for production planning in a context where the production campaigns have a fixed duration. The aim is to fix the campaign duration on a single paper machine of a North American fine paper mill. The planning model is used to anticipate the cost of planning under different fixed duration production campaigns. The volume produced of each product may however vary between cycles. The difficulty in this problem is raised by the sequence dependent setups between product batches on the paper machine.

Chauhan et al. (2008) deal with tactical demand fulfillment of sheeted paper in the fine paper industry. The authors adopt a sheet-to-order strategy, which means that parent rolls are produced to stock. The sheeting occurs subsequently upon receipt of customer orders. A model is proposed to find the assortment of parent rolls to keep in stock in order to minimize expected inventory holding and trim loss costs. When tested on real data from one of the largest fine paper mill in North-America the model proved capable of reducing inventory holding costs substantially while at the same time achieve a slight reduction in trim loss cost.

At the operational level, Rizk et al. (2006a) present a model for planning the production on multiple machines in a single mill. The production planning is integrated with the distribution planning to a single distribution centre. The production of intermediate products and final products is coordinated. The production of intermediate products is considered to be the bottleneck in the production line, whereas no capacity constraint is considered for the converting to final products. Economies of scale in transportation is accounted for through a piecewise linear function. Results presented from a real case coming from one of the largest uncoated free sheet producers in North-America shows considerable savings when production and distribution decisions are optimized all together as compared to optimize distribution planning first, and then, constrain the optimization of the production planning. In Rizk et al. (2006b) the previous model is expanded to include multiple distribution centers.

Another case in which multiple stages of paper manufacturing are planned simultaneously is presented in Murthy et al. (1999). In this case, the planning includes allocation of orders to machines (possibly at different locations), sequencing of the orders on the machine, trim scheduling for each machine, and load planning. The authors report several real-world implementations of the planning system in the US based company Madison Paper Inc with substantial savings in trim loss and distribution costs. Keskinocak et al. (2002), Menon and Schrage (2002) and Correira et al. (2004) also contributed to this idea of integrated scheduling and cutting approaches in a make-to-order strategy. In Martel et al. (2005), a general discussion of the synchronized production distribution problem is presented, defining the planning problems under three different strategies: the make-to-stock, the sheet-to-order and the make-to-order.

Bredström et al. (2005) deals with operative planning of pulp distribution. The model focuses on routing and scheduling of vessels which are coordinated with other available means of transportation such as trucks and rails.

Bergman et al. (2002) deals with roll cutting at paper mills. Roll cutting is a well known academic problem for which there are efficient solution methods. However, in an industrial setting there are many practical issues to consider e.g. limited number of knives in the winder, products needs to be in the same pattern or not, different due dates for products, limited inventory space etc. Another practical issue is given a minimum number of rolls needed there is an objective to use as few cutting patterns as possible. This to limit set up costs and times. In this article a system taking into account these issues is described and tested on a set of case studies. Other roll cutting models particularly suited for the paper industry are presented by Goulimis (1990) and Sweeney and Haessler (1990).

Finally, Flisberg et al. (2002) describes an online control system for the bleaching process at a paper mill. The problem is to decide the chemical charges in a number of bleaching steps. The objective with the system is to support operators to minimize the chemical usage (i.e. cost of chemicals) and improve the spread of the brightness of the pulp before it reaches the paper machines.

4.3. Lumber, panel and engineered wood

The work of Vila et al. (2006, 2007), which proposes a generic methodology to design international production-distribution networks for make-to-stock products with divergent manufacturing processes, has been applied to the lumber industry. In their papers, the authors have addressed the strategic planning decisions of the lumber industry under stochastic demand and prices. The aim is to provide a supply chain design (opening and closing of mills, technology investment and market decisions including product substitution) that will favorably position the enterprise to win anticipated high value market shares. Three different sub-markets are considered in the model: contracts, vendor managed inventory and spot markets. In Vila et al. (2007), the production-distribution network design problem is formulated as a two-stage stochastic program with fixed recourse. A sample average approximation method (SAA) (Santoso et al. 2005), based on Monte Carlo sampling techniques, is used to solve the model. Here the forestry decisions are externally made and modeled as supply constraints into the model.

As for the secondary wood product, Farrell and Maness (2005) developed a relational database approach to create an integrated linear programming-based decision support system that can be used to analyze short-term production planning issues. The DSS is generic and able to analyze production strategies in the highly dynamic environment of in a wide variety of secondary wood product manufacturers.

On the timber and lumber side, Maness and Adams (1993) propose a model to integrate the bucking and sawing processes. The model is formulated as a mixed integer program. This model, while linking log bucking and log sawing for a specific sawmill configuration, accounted for inelastic demand by controlling price–volume relationships. The system developed takes into account one sawmill, with raw material distribution, over one planning period and a deterministic final product demand. Maness and Norton (2002) propose an extension to this model to take into account several planning periods.

Reinders (1993) develops a decision support system for the strategic, tactical and operational planning of one sawmill (the operations of bucking and sawing are done in the same business unit). The model does not take into account other processes like planing and drying.

To tackle the impact of different strategic design and planning approaches on the performance of lumber supply chains (Frayret et al., 2007; D'Amours et al., 2006; Forget et al., 2007), propose the development of an agent based experimental platform. The platform can model different configurations of lumber supply chains (e.g. many mills and generic customer/supplier relations). It models the sawmilling processes as alternative one-to-many processes constrained by bottleneck capacity. The drying processes are also viewed as one-to-many processes where green lumbers are grouped following specific rules and extended drying programs including air drying are considered. Finally, the finishing processes are modeled as one-to-many processes with setup constraints.

The authors use different business cases to validate the system and the proposed specific planning models (e.g. linear programming, constraints programming and heuristics). An industrial implementation was also conducted to test the scaling capacity of the platform.

Further, simulations where conducted to evaluate different strategies for the lumber industry under different business contexts. The simulator can account for many sawmills, drying and finishing facilities. The procurement of wood is set as constraints. Demand patterns can be stochastically generated following different spot market and contract based customer behaviors. Although the experimental platform can help make strategic and tactical decisions, it simulates the supply chain at the operational level, planning for every shift or day, the procurement, production and distribution operations to be conducted following.

As for tactical planning of the lumber, panel and engineered wood products, a few contributions are found in the literature. They illustrate the challenge of integrating the different business units of the lumber supply chain (Lidén and Rönnqvist, 2000; Singer and Donoso, 2007), of the wood supply chain of furniture mills (Ouhimmou et al., 2007) and the yard to customer supply chain of an OSB company (Feng et al., 2007).

Lidén and Rönnqvist (2000) introduce an integrated optimization system, CustOpt, allowing a wood supply chain to satisfy the customers demand at minimum cost. The model considers the bucking, sawing, drying, planing, and grading processes. The integrated system is used as a decision support tool at the tactical level (3 months planning horizon). The system was tested using two to five harvesting districts, two sawmills and two planing mills.

In a similar perspective, Singer and Donoso (2007) recently present a model for optimizing planning decisions in the sawmill industry. They model a supply chain composed of many sawmills and drying facilities. Storage capacities are available after each process. In this problem, each sawmill is an independent company, therefore lucrative as well as unprofitable orders must be split as equitably as possible. The models allow transfers, externalizations, production swaps and other collaborative arrangements. The proposed approach was applied at AASA, a Chilean corporation composed of 11 sawmills. The results prescribe transfers, incurring explicit transportation costs. It also recommends some plants focusing almost exclusively on upstream production stages while leaving the final stages to others.

Ouhimmou et al. (2007) present a model for planning the wood supply to furniture assembly mills. The model addresses the multi-sites and multi-periods planning of procurement, sawing, drying, and transportation. The MIP based model is solved both optimally using CPLEX and approximately using time decomposition heuristics assuming the demand is known and dynamic over the planning horizon. The model is applied to an industrial case reporting on high cost reduction potential. The aim is to set procurement contracts, inventory target over the year for all products in all mills, mill-to-mill relations, outsourcing contracts and sawing policies.

Feng et al. (2007) apply the concept of sales and operations planning (S&OP). They incorporate sales decisions to investigate the opportunities of profitably matching and satisfying the demands with the given supply chain capabilities of production, distribution, and procurement. More precisely, they propose a series of mathematical programming models to evaluate the benefit of the integrated S&OP planning over the traditional decoupled planning process in a context of a real OSB manufacturing supply chain system within a make-to-order environment. The integrated S&OP planning process shows higher benefit when procurement costs increase or market prices of final product decrease, meaning that difficult economical conditions call for integrated planning.

At the operational level, the cutting problem is often critical. Whether one is dealing with timber, hardwood or softwood lumber, paper, panel and engineered wood products, the optimal cutting of the incoming products is crucial in terms of material yield management as well as demand satisfaction. The general literature provides many models to deal with cutting problems. In the forest product industry, issues with defects and grading are to be considered raising needs for tackling difficult 2D or even 3D problems. An example of such problem relates to finding the optimal cutting pattern to obtain dimension parts in *Pinus Radiata* is reported in Todoroki and Rönnqvist (2002). As production rates are typical high in the industry, the different cutting problems are to be solved rapidly.

In the furniture industry, many contributions have dealt with the optimization of the cutting list at the mill level in order to meet demand and minimize wood lost (Buelmann et al., 1998; Carnieri et al., 1993; Hoff, 1997). The cutting lists define how to group the dimension parts together so the associate cutting processes can be performed using as little wood boards as possible.

4.4. Heating

To provide this energy, an increasing number of heating plants are being implemented. A planning model for this is presented in Gunnarsson et al. (2004). These plants are normally operated by the local communities. For the supply of fuel, the heating plants enter into contracts through a competitive bidding process where contracts are awarded to one or several entrepreneurs. A contracted company is obliged to deliver a certain amount of energy, specified in MWh, for each time period (normally one month). Several fuel types exist that can be used in the heating plants and one important type is forest fuel. Forest fuel can be either forest residues that are chipped (converted into small pieces), by-products arising from sawmills such as sawdust, or wood without other industrial use. Forest residues are branches and tops that are left on harvest areas after the logs have been transported to saw mills or pulp mills. Once the residue is dried, it is forwarded, collected into piles in the harvest area. Thereafter, it can be chipped directly at the harvest area by mobile chippers, or transported to terminals or heating plants where it is chipped at some stage by a fixed or a mobile chipper. The transportation cost constitutes a large proportion of the overall handling costs, and there is a trade-off between chipping directly at harvest areas or at terminals. It is typically cheaper to chip at terminals, but the transportation of non-chipped forest residues is more expensive, as compared to chipped products. With the increased energy prices, trade in emission rights and different tax systems, the usage of pulp logs directly at heating plants has increased. This competition between pulp and paper producers and heating plants is expected to grow in the future.

5. Collaborations in the Forest Product Industry

Collaboration issues are tightly linked to any supply chain discussion. However, it is only recently that OR has been used to evaluate its potential for the forest product industry raising interesting research questions. The following contributions provides example of how the value of collaboration in the forest product industry has been recently addressed.

In the forest, when many companies are recuperating their wood allocation from uneven aged forest owned by the state, they often need to agree on a common harvesting plan. Beaudoin et al. (2007b) addressed this problem proposing collaborative approaches to help the negotiation process converge to a profitable equilibrium. He first proposed a planning approach to help each company establish its own set of optimal plan in regard of different scenarios. Then, he illustrated the value of collaborating to set the harvesting schedule.

Collaboration benefit were also explore through the transportation of logs to mills. Often, many enterprises are operating in different parts of the country proving some opportunities to optimize the backhauling. This opportunity was seen in different parts of the world and was tackled with the specific wood allocation and trucking constraints of each region. Frisk et al. (2006b) (Sweden), Palander and Vaatainen (2005) (Finland), and Audy et al. (2007) (Canada), all worked on different version of this problem. They also raised the challenging problem of proposing models to share risks and benefits.

Finally, collaboration between a paper mill and a customer was also explored by Lehoux et al. (2007). Four different integration approaches were simulated and optimized, starting by the traditional make-to-order, then moving toward continuous replenishment, vendor managed inventory (VMI) and finally Collaborative Planning Forecasting and Replenishment (CPFR). For all the tested scenarios, CPFR showed the greatest benefits when a global perspective is considered. However, under specific economical conditions, the customer may gain more benefit from a continuous replenishment approach while the producer gain more benefit from the CPFR approach.

6. Conclusion

This paper has presented a review of the wood fiber flow from forest to customer. It has described the major supply chains of the forest product industry which are the forest, the pulp and paper, the lumber, panel and engineered wood and the energy supply chains.

The challenges of integrating the different supply chain decisions are first discussed in general terms and second more specifically for each of the supply chains described in this paper.

A non exhaustive literature review is presented with the aim to mainly illustrate the main and key planning problems of the industry. The review showed that very little work has been done to link the forest supply chain to the other forest products supply chains. This is still a major challenge for the industry and researchers should aim to develop new models to support this integration.

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