Using Operational Research for Supply Chain Planning in the Forest Products Industry

Sophie D'Amours
Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport (CIRRELT), FORAC Research Consortium, Université Laval, G1K 7P4, Québec, Canada

Mikael Rönnqvist
The Norwegian School of Economics and Business Administration, Bergen, Norway and The Forestry Research Institute of Sweden, Uppsala, Sweden

Andres Weintraub
Department of Industrial Engineering, University of Chile, Santiago, Chile

Abstract—Over the years, Operational Research (OR) has been used extensively to support the forest products industry and public forestry organizations (e.g., governments, environmental protection groups) in their respective planning activities concerning the flow of wood fiber from the forest to the customer. The applications deal with a wide range of problems, ranging from long-term strategic problems related to forest management or company development to very short-term operational problems, such as planning for real-time log/chip transportation or cutting. This paper presents an overview of the different planning problems and reviews the past contributions in the field of forestry, with a focus on applications and problem descriptions. In the context of the 50th anniversary of the Canadian Operational Research Society, this paper also recognizes the contributions of many Canadian researchers to the field of forestry management.

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

1. INTRODUCTION

Although supply chain planning has helped to improve the performance of many companies, the challenge of integrating the different planning problems still remains. This is the case when the procurement, production, distribution and sales activities need to be synchronized throughout a set of independent business units (e.g., entrepreneurs, carriers, sawmills, pulp and paper mills), their suppliers and their customers. Forest product supply chains are generally composed of many interconnected business units that are constrained by their divergent processes. For example, one supply chain can include the producers who manage a mix of species in the forest, the various entrepreneurs who convert these trees into logs or chips, the sawmills that cut the logs into boards or dimension parts, and the pulp and paper mills that use the wood chips to create reels of paper that are then cut into smaller product rolls or sheets. These varied many-to-many processes make the task of integrating the procurement, production, distribution and sales activities very complex, given that these activities are always bounded by the tradeoffs between yield, logistical costs and service levels.

In addition to integrating the varied activities, it is also crucial for supply chain planning to integrate strategic, tactical and operational decision-making. Because of the size of the problems, due to the number of products, processes, suppliers, customers and time periods, decomposition techniques and/or hierarchical planning approaches are typically needed. Strategic decisions impose constraints on the tactical planning process, and the ensuing tactical decisions impose constraints on the operational planning process. In the forest products industry, supply chain planning is particularly challenging since strategic planning for forest management may span more than 100 years, while operational planning for cutting trees or logs may involve only fractions of a second.

Several surveys exploring the different perspectives on the forest product supply chain can be found in the literature today. Rönnqvist (2003), Martell et al. (1998) and Epstein et al. (1999) all reviewed the contribution of OR to the forestry industry, focusing on issues related to forest management, harvesting and transportation to wood-consuming industries. More recently, Carlsson et al. (2006 and 2008) completed these surveys by concentrating on the planning and distribution of forest products such as paper, lumber, engineered wood products and bio-fuel. Weintraub and Romero (2006) have included environmental and implementation issues.

In general, the quality of forest management and forest operations has an immense direct impact on the performance of the different wood fiber supply chains. This impact has frequently been observed and reported by researchers working to optimize forestry decision-making about such diverse elements as silviculture treatments, harvesting sectors and scheduling, forest road construction, wood allocation and transportation. The *Handbook on Operations Research in Natural Resources* (Weintraub et al., 2007) presents many models designed to improve integrated planning in the forestry business sector, especially for private forest owners.

The literature in the forestry domain can be divided into two categories. The first category focuses on forestry, particularly forest management, harvesting and transportation, and the second, on supply chain planning for the different products/markets, such as pulp and paper, lumber, engineered wood products and bio-fuel. This paper presents an overview of these two categories, highlighting key examples of forest planning problems. It also supports the development of models that would better integrate the forestry supply chain into the other forest products supply chains. This paper does not pretend to be an exhaustive review of the literature.

The paper is organized as follows: The second section describes the flow of wood fiber, from the forest to the market, and presents the main production processes and approaches. Section 3 reviews strategic, tactical and operational supply chain planning decision levels for the forest products industry and explains them in general terms. Section 4 covers the literature about forest products, including a discussion of the pulp and paper, lumber, engineered wood, and energy supply chains. Since collaboration appears to be an important aspect of supply chain management, Section 5 presents recent works addressing the challenge of collaboration and profit/loss sharing. The final section offers our concluding remarks.

2. FIBER FLOW

The flow of the many different products in the wood fiber supply chain is shown in Figure 1. Forest products supply chains can be seen as large networks through which wood fiber is gradually transformed into consumer products. In the various supply chains, the production network is linked to a procurement network that starts in the forest. The production network is also linked to a distribution network that ends with merchants or retailers, who, along with end users, constitute the sales network. Different modes of transportation (e.g., trucks, trains and ships) are used to transport the various products from one network to the other.

Forest products are thus transformed and distributed as they flow through the supply chain. The transformation activities involve generic many-to-many processes, which consume a set of input products that are combined in different ways (e.g., recipes in the pulp and paper industry) or cut according to different cutting patterns (e.g., bucking or sawing patterns) in order to produce a set of output products. These output products are classified as either co-products or by-products. Co-products are demand-driven products; by-products are the secondary results generated by the process—usually low value products (e.g., bark or saw dust)—and are sold on other markets. In many circumstances, the transformation is done through alternative processes (e.g., recipes or cutting patterns), in which case the planning decisions must also select the processes to be used.

The different wood product firms typically own a set of business units that are involved in the transformation and distribution of forest products. When such a firm owns units covering the gamut from harvesting activities to distribution activities, it is said to be integrated. Certain large international companies, in addition to encompassing a wide range of activities, are also active in all of the different markets shown in Figure 1. For example, Stora Enso, an international corporation with its head office in Finland, has many interrelated supply chains.

The forest supply chain must provide trees suitable for different uses. Providing suitable trees involves dealing with a variety of issues, ranging from strategic forest management (e.g., land management and silviculture treatments) to operational tasks related to harvesting and transportation. Forest supply chain planning means dealing with a very long-term 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 management) and the type of land tenure (e.g., public or private), the planning problems may differ from country to country and from region to region. Despite these differences, there is one commonality: the need for greater integration of the forest supply chain and industrial supply chains (i.e., pulp and paper, lumber and engineered wood, energy).

Harvesting includes the following main phases. The trees are cut and branches are removed. Then, the tree is bucked (or cross-cut) into logs of specific dimensions and quality, which can be done in the harvest sectors or in lumber yards. Trees, or logs, are then transported directly to mills or to terminals for intermediate storage. The harvesting is done by groups of harvest crews and the transportation by one or several transport companies. The global planning for harvest and transportation is often done together.

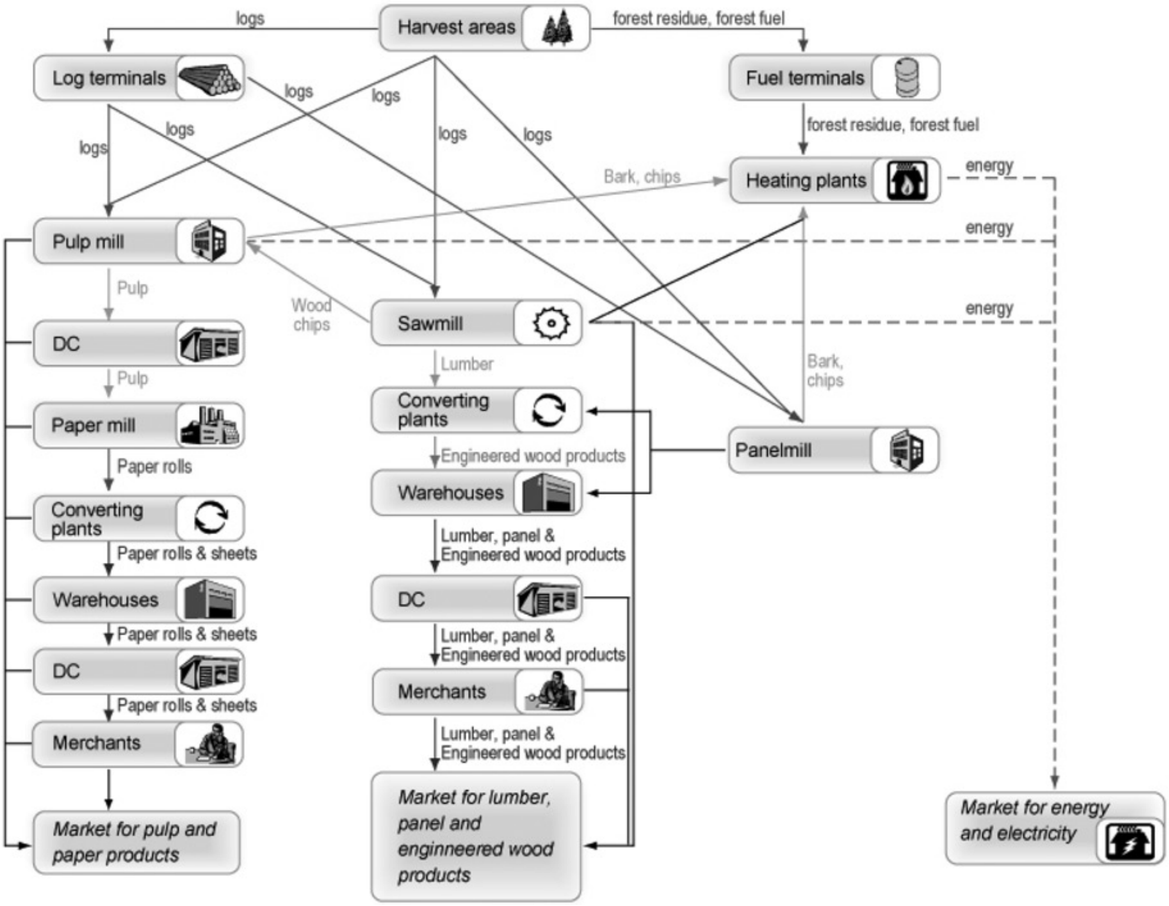

Figure 1. The different supply chains of the forest products industry

2.1 Fiber Flow in the Pulp and Paper Supply Chains

As the logs or chips travel through the pulp and paper supply chain, they are transformed first into pulp and then into paper, which is then formed into commercial rolls or sheets. In pulp production, the fibers are mixed with chemicals according to a specific recipe to produce the different pulp grades. Recycled paper is often introduced to the pulp, which is then used to produce jumbo reels of paper of a specific grade, finish, base weight and color. The jumbo reels are cut into rolls, which can be either sold directly on the market and or sheeted for printing and writing paper products. From the mills, the paper is distributed either directly or through a network of wholesalers, distributors and merchants. Customers vary with the type of paper; for example, printers may buy newsprint; retailers may buy fine paper; and food chains, packaging materials. A typical pulp and paper company owns many mills. This pulp and paper supply chain uses all modes of transportation: trucks, trains and ships are used to transport logs or chips from the forest to the pulp mills; though pulp products may be transported by truck, they mostly travel by train or ship; finished paper is usually moved by train or truck.

2.2 Fiber Flow in the Lumber, Panel and Engineered Wood Supply Chains

The lumber, panel and engineered wood industries transform the logs into boards to produce lumber and dimension parts or into flakes to produce panels. Boards and panels are used as components for engineered wood products, which are mainly used in construction or decoration.

Lumber is produced in stages. First, the logs are sawn into boards in sawmills. In modern 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. The boards are then dried in dry kilns, either by batch or by continuous process, and are grouped according to specific configurations in order to maximize the quality of the output. Finally, the boards are planed on finishing lines, where setup constraints affect the finishing process. The setup times are mainly due to emptying the buckets containing the finished products.

Panels are produced from wood flakes, which are dried, glued and pressed together. The wood flakes are cut from logs that have been stored in ponds so they would soften. The flakes are then mixed with resin and spread to form a mattress, which is then cut to length. The final board is produced by pressing this mattress under heat conditions. When the panels are used to make engineered wood products (e.g., prefabricated wood I-beams), they are again cut into smaller dimensions to meet specifications.

Engineered wood products are typically produced by assembling lumber and panels. They are used for structural parts in residential and non-residential constructions (e.g., flooring or roofing systems). Many standards regulate lumber, panel and engineered wood products. For example, in North America, softwood lumber must conform to the NLGA (National Lumber Grade Authority) certification that defines the grades, or quality, for softwood lumber of certain dimensions, while hardwood lumber must conform to the NHLA (National Hardwood Lumber Association) grading rules.

Customers exhibit different buying practices, all of which are greatly affected by the variation of the spot market prices. These practices can be grouped into three different categories: spot market, vendor-managed inventory and contract-based. The vendor-managed inventory and contract-based approaches usually offer a financial advantage to the producer in exchange for guaranteed deliveries.

2.3 Fiber Flow in the Bio-fuel Supply Chain

The energy industry uses forest product residues to produce energy. Forest biomass is supplied directly from the forest or from the mills. This biomass, which serves as bio-fuel to produce the energy, can be transported bulk, bundled or chipped. Chipping can be done in the forest, at the intermediate storage terminals or at the heating plants. Some chemical processes can be used to transform the residues into specific bio-fuels, such as ethanol. The energy supplied can be used to satisfy public needs (e.g., heating plants that supply residential and industrial sectors with hot water for heating) or industrial needs (e.g., drying kilns). As the cost of fuel rises, using wood residues for energy is becoming an increasingly attractive alternative.

3. SUPPLY CHAIN PLANNING IN THE FOREST PRODUCTS INDUSTRY

Supply chain planning in the forest products industry encompasses a wide range of decisions, from strategic to operational. The following subsections illustrate the scope of these decisions and the specific issues of supply chain planning in the Forest Products Industry.

3.1 Strategic Planning

Strategic, or long-term, planning in the forest products industry is indeed very long-term. For example, the rotation of forest growth can take more than 80 years, and a new pulp or paper mill is normally intended to last more than 30 years. Thus, strategic decision-making includes making choices related to forest management strategies, silviculture treatments, conservation areas, road construction, the opening/closing of mills, the location/acquisition of new mills, process investments (e.g., machines, transportation equipment, information technology), product and market development, financial and operational disclosure, planning strategies (e.g., make-to-stock, make-to-order, cut-to-order) and inventory location (e.g., location of decoupling points and warehouses).

The planning approach chosen has a major impact on all investment decisions. For example, the capacity needs and the type of equipment required to support a make-to-stock strategy would be different than those needed to support a make-to-order strategy. Therefore, the planning approach defines important parameters with respect to the necessary technology, capacity, inventory levels and maximum distances to customers. Such decisions naturally involve evaluating how the investment will fit into the whole supply chain, including deciding which markets are available for the products based on anticipated market trends, how the distribution of the products should be carried out and at what cost, and how the production units should be supplied with the necessary wood fibers (i.e., wood or pulp). Other elements, such as energy supplies, might also be crucial.

The type of forest land tenure may also affect the way supply chain strategic decisions are made. Wood could come from public lands, private lands or both, with each type requiring different procurement programs. Other factors may also have to be considered. For example, governmental rules governing the amount of forest land to be set aside for bio-diversity purposes, recreational use and/or carbon sequestration must be taken into account in any decision.

The literature about strategic supply chain planning provides a broad and rich examination of the domain and proposes a variety of different solution methods. However, very few articles focus on divergent alternative production processes or mixed demand behaviors (e.g., spot and contract-based demands). Specific methodological contributions are needed to remedy this lack. In addition, very little research in strategic supply chain planning pertains specifically to the forest products industry (FPI). The scarcity of research in this domain underlines the demand for knowledge about FPI implementation and the need to integrate the decisions related to forest management and forest operations into the other downstream supply chain planning chains decision-making processes.

3.2 Tactical Planning

Following strategic planning, the next level in the hierarchical planning structure is tactical or mid-term planning. Tactical planning is slightly different depending on whether a forest management problem or a production/distribution planning problem is being addressed. In forest management, hierarchical planning approaches are widely implemented as they permit the tactical planning problem to be initially addressed without taking spatial issues into account. Once this has been done, the problem is then tightly constrained spatially. While strategic forest management planning problems generally span 100 years, tactical planning problems are often reviewed annually over a five-year planning period.

In planning problems dealing with production/distribution issues, tactical planning normally addresses the allocation rules that define which unit or group of units is responsible for executing the different supply chain activities or what resources or group of resources will be used. It also sets the rules in terms of production/distribution lead times, lot sizing and inventory policies. Tactical planning allows these two types of rules to be defined through a global analysis of the supply chain. Tactical planning also serves as a bridge between the long-term comprehensive strategic planning and the short-term detailed operational planning that has a direct influence on the actual operations in the chain (e.g., truck routing, production schedules). Tactical planning should also ensure that the subsequent operational planning conforms to the directives established during the strategic planning stage, even though the planning horizon is much shorter. Other typical tactical decisions concern allocating customers to mills and defining the necessary distribution capacity. The advanced planning required for distribution depends on the transportation mode. For example, ship and rail transportation typically need to be planned earlier than truck transportation.

Another important reason for tactical planning is tied to the seasonality of the supply chain, which increases the need for advance planning. Seasonality has a great influence on the procurement stage (i.e., the outbound flow of wood fiber from the forests). One reason for this seasonality is the shifting weather conditions throughout the year, which can make it impossible to transport logs/chips during certain periods due to a lack of carrying capacity on forest roads caused by the spring thaw, for example. In many areas of the world, seasonality also plays a role in harvesting operations. In the Nordic countries, for example, a relatively small proportion of the annual harvesting is done during the summer period (July-August). During this period, operations are instead focused on silvicultural management, including regeneration and cleaning activities. A large proportion of the wood is harvested during the winter when the ground is frozen, thus reducing the risk of damage while forwarding (or moving) the logs out of the forest. Seasonality can also affect the production stage (e.g., in Nordic countries, hardwood drying times can vary over the season) or the demand process (e.g., again in Nordic countries, most construction projects are not conducted during the winter period).

Another area in which tactical planning can be useful is budget projection. Most companies execute an important planning task when projecting the annual budget for the following year, deciding which products to offer to customers and in what quantities. In the process of elaborating these decisions, companies need to evaluate the implications of their decisions on the whole supply chain (procurement, production and distribution) with the aim of maximizing net profits. Shapiro (2001) has suggested that such tactical planning models be derived from the strategic planning models, in which the 0-1 variables related to the strategic decisions are fixed and the planning horizon is extended to a multi-period (multi-seasonal) horizon. Solving the model can then provide insights into how the budget must be defined for each of the business units within the supply chain.

3.3 Operational Planning

The third level of planning is operational or short-term planning, which is the planning that precedes and determines real-world operations. For this reason, this planning process must adequately reflect the detailed reality in which the operations take place. The precise timing of operations is crucial. It is generally not enough to know the week or month that a certain action should take place; the time period must be defined in terms of days or hours. Operational planning is usually distributed among the different facilities, or units in the facilities, due to the enormous quantity of data that has to be manipulated at the operational level (e.g., number of Stock Keeping Units (SKU) and other specific resources).

Within the production process, one type of operational planning problem deals with cutting and must be solved by many of the wood product mills (e.g., lumber, dimension parts, and pulp and paper mills). Scheduling the different products moving through the manufacturing lines is also a typical operational planning problem, as is process control involving real-time operational planning decisions. Process control is particularly critical in the pulp and paper industry as the characteristics of the output products depend greatly on the precision of the chemical-fiber mix. Another type of operational planning problem deals with the problems related to transportation, specifically the routing and dispatching done at several points in the supply chain. For instance, it is necessary to route the trucks used for hauling wood from the forest to the mills or for shipping finished products from mills to customers or distribution centers.

Table 1 presents an illustrative summary of the strategic, tactical and operational planning decisions needed in the pulp and paper industry. This supply chain planning matrix was proposed by Carlsson et al. (2006) based on a series of case studies conducted with the Swedish pulp producer Södra Cell (Carlson et al., 2005).

3.4 Methods

A full range of OR methods have been proposed to support planning problems in the forest products industry. Rönnqvist (2003) presented a series of typical planning problems found in the forest products industry, with comments about the time available for solving each of these problems. He observed that, while operational planning problems usually need to be solved rapidly, within seconds or minutes, strategic planning problems can be solved over a longer period of time, sometimes taking many hours. For this reason, heuristics, meta-heuristics and easy-to-solve network methods are generally used for operational problems, whereas Mixed Integer Programming (MIP)

TABLE 1.
Supply chain planning matrix for the pulp and paper industry (Carlsson et al. (2006)) (DC: Distribution Center)

	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 and investment strategies (e.g., roads, construction, trucks, wagons, terminals, ships)	• Location decisions • Outsourcing decisions • Technology and capacity investments • Allocation of product families to facilities • Order penetration point strategy • Investments in information technology and planning systems (e.g., advance planning and scheduling technologies, ships)	• Warehouse location • Allocation of markets/customers to warehouses • Logistics resource investments (e.g., warehouses, handling) • Contracts with logistics providers • Investments in information technology and planning systems (e.g., warehouse execution)	• Selection of markets (e.g., location, segment • Customer segmentation • Product-solution portfolio • Pricing strategy • Service strategy • Contracts • Investments in information technology and planning systems (e.g., On-line tracking systems, CRM)
Tactical	• Sourcing plan (log class planning) • Aggregate harvesting planning • Route definition and transshipment yard location and planning • Allocation of harvesting and transportation equipment to cutting blocks • Allocation of products/blocks to mills • Yard layout design • Log yard management policies	• Campaign duration • Product sequencing during the campaigns • Lot-sizing • Outsourcing planning • Seasonal inventory target • Parent roll assortment optimization • Temporary mill shutdowns	• Warehouse management policies (e.g., dock management) • Seasonal inventory target at DCs • Routing (Ship, 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 products and customers to mills • and DCs
Operational	• Detailed log supply planning • Forest to mill: daily carrier selection and routing	• Daily production plans for pulp mills/paper machines/winders/sheeters • Mill to converter/DC/customer: daily carrier selection and routing • Roll-cutting • Process control	• Warehouse/DC inventory management. • DC to customer: daily carrier selection and routing • Vehicle loads	• Available to promise consumption • Rationing • Online ordering • Customer inventory management and replenishment

and stochastic programming methods are better for tactical and strategic planning problems. Many of the OR models are implemented in diverse industrial Decision Support Systems (DSS), which are often integrated into application-specific databases holding all the information needed for the models and the Geographical Information Systems (GIS) used to visualize the input data and results.

4. LITERATURE REVIEW

In this section, different papers are discussed in terms of the different supply chains and planning problems, as they were presented in Sections 2 and 3. Strategic concerns are discussed first, tactical concerns second and operational concerns last. Specific contributions dealing with forest management and harvesting operations are included in the review as they address important forest management issues and impact the supply chain planning (e.g., environmental concerns and fire).

4.1 Forest Management and Harvest Operations

4.1.1 Forest Management

The forest supply chain is a very strategic component of the three main supply chains described in this paper (i.e., pulp and paper; lumber, panel and engineered wood; bio-fuel). The various business units in the chain are typically extremely widespread geographically since they deal with different operations (e.g., planting, thinning, road construction, harvesting, storage and transportation). In the forest supply chain, it is first necessary to solve the problem of allocating wood for different uses. In terms of economics, the problem then becomes a question of distributing the wood to the different supply chains. The decisions range from strategic decisions to operational decisions. The long-term strategic decisions aim to attain societal targets defined in order to meet sustainable socio-economic development. Some of the strategies decided upon span several forest rotations, which means some countries have to establish plans covering more than 100 years. Over time, these plans have a great impact on the quality and volume of the available fiber.

Strategic forest management puts the emphasis on the relationship between decisions connected to forest use (e.g., harvesting areas, allocations, silvicultural treatments) and their different socio-economic consequences (e.g., environmental problems, non-declining yield, continued employment, forest access and industrial competitiveness). Numerous models have been developed to aid forest managers and public forestry organizations in their decision-making. Some of these models are based on operational research (e.g., harvest planning, road construction and maintenance planning), while others are based on simulation (e.g., simulations of growth or ecological impact). Economic models help to connect fiber availability to the value of the forest products (Gunn, 2007). On public land, forest management regimes are established by the government. Since multiple criteria need to be considered during decision-making, most governments use simulation to evaluate the impact of different forest management strategies (Davis et al., 2001).

During the 1970s and 1980s, linear programming (LP) models, such as the FORPLAN used by the USDA Forest Service, flourished. LP models allow information about growth, biodiversity, spatial requirements and requirements for protected area to be taken into account. In such models, forest management strategies are treated as constraints (Gunn, 2007), though spatial constraints have not yet been considered. For example, these models normally include a set of non-declining yield constraints.

Once the forest management strategy has been established, the tactical and operational planning decisions are made, integrating the needs of the different supply chains. The harvesting sectors and the transportation infrastructure are defined precisely, all subject to spatial constraints in addition to the constraints established by the strategic plan. Simulation models permit the spatial location and growth of each block to be represented (Bettinger and Lenette, 2004), thus allowing multiple plans to be evaluated in light of spatial issues.

Allocating wood fiber to producers appears to be a universal problem. In countries in which most forests are privately owned, flexibility seems to be greater, since allocation decisions can be made at the same time as transportation decisions. However, given the range of possibilities and the enormous quantity of information that must be managed when planning forestry operations, many researchers favor a hierarchical planning approach. In the first step, the treatments are decided with respect to volume, and these decisions become constraints for spatial planning in the second step (Weintraub and Cholaky, 1991; Hof and Pickens, 1987; Church et al., 1994).

4.1.2 Spatial and Environmental Concerns

With the advent of GIS and the associated spatial data, integrated forest management and harvest planning practices have begun to show increasing concern for spatial relationships and environmental conditions. Particular issues of interest include promoting the richness and diversity of wildlife, creating favorable habitats for flora and fauna, ensuring the quality of soil and water, preserving scenic beauty, and guaranteeing sustainability. Tactical models seek to address these issues, implicitly or explicitly, by structuring the necessary constraining relationships and limiting spatial impact.

One of the primary ways that spatial relationships and environmental conditions have been modeled at the tactical level is by using adjacency restrictions with green-up requirements. Specifically, a maximum local impact limit is established to restrict local activity for a given period of time. In the case of clear cutting, for example, this corresponds to a maximum open area, which is imposed on any management plan. Another important example for wildlife is the requirement that patches of mature habitats (i.e., contiguous areas of a certain age) must be maintained to allow animals to live and breed. To ensure this, potential areas must be grouped to form patches (Öhman and Eriksson, 1998).

A number of models incorporate the maximum open area and adjacency constraints. They can be divided into two groups: 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 open area restriction (Murray 1999). In the second approach, the harvest areas are not predetermined, but are generated using smaller building blocks. With such a model, it is possible to harvest adjacent areas, but the restrictions on maximum open areas must be dealt with directly when formulating the areas. The second approach has the clear advantage of including many more possibilities (McDill et al., 2002; Murray and Weintraub, 2002; Goycoolea et al., 2003).

Although strategic forest management decisions are supported by timber supply models, such models typically lack the ability to integrate the transformational capacity of the forest owners or their customers (e.g., sawmills, pulp mills) and the value and cost of forest products, both of which are tightly linked to the location of the mills and the markets. Gunn and Rai (1987) examined this issue and proposed a model supporting long-term forest harvest planning in an integrated industry structure.

4.1.3 Harvesting and Transportation

Tactical planning in forest management is typically associated with making decisions on how to treat standing timber over a horizon ranging from several years to several decades. The term, *forest operations*, refers to the actions that affect harvest operations directly (Epstein et al., 2007a). Historically, tactical model decision variables are related to the selection and sequencing of stands, or cutting blocks, for harvesting in order to satisfy temporal demands for timber. In addition, road engineering is also a necessary component of tactical planning, since the industry is dependent on an efficient road network to provide access to harvest areas. Thus, the associated costs of road engineering and harvesting impact the viability of management plans. For these reasons, tactical planning generally involves the use of mixed integer linear programming to model decisions on when and where timber should be harvested, as well as which roads should be built or maintained.

One of the classic studies of road building (which in and of itself is a strategic problem) was done by Kirby et al. (1986); this study saw significant use by the US Forest Service in the ensuing years. The deployment of the forest road system and the selection of the transportation infrastructure are strategic issues, often resolved through MIP problems (Epstein et al., 2007b). Richards and Gunn (2000) clearly explained the challenges of designing a forest road network. Andalaft et al. (2003) have presented a model called OPTIMED, designed to simultaneously optimize the harvesting plan, seasonal storage and road network deployment over a 2- to 3-year planning horizon. In this study, the MIP problem is solved by strengthening the formulation and using Lagrangean relaxation. Olsson (2004) and Henningsson et al. (2007) have recently presented MIP models that include decisions about restoring existing forest roads and transportation in order to provide access to available harvest areas during the spring thaw when only certain roads are practicable. The model used by Henningsson et al., (2007) is the basis for the decision support system, RoadOpt (Frisk et al., 2006a), developed by the Forestry Research Institute of Sweden.

Transportation is a major part of forest operations, constituting up to 40% of the operational costs. In some cases, harvest planning is combined with transportation and road maintenance planning, with an annual planning horizon. A MIP model to solve this multi-element planning problem has been proposed by Karlsson et al. (2004). A previous article by the same authors (Karlsson et al., 2003) presented a model that integrated the handling of crews, transportation and storage. Other important issues in transportation include the possibility of integrating truck transport with other modes of transportation, specifically ship and train (Forsberg et al., 2005; Broman et al., 2006). Transportation operations provide the operational link between the forest supply chain and other supply chains. Since transportation costs account for a large proportion of the total cost of wood fiber for a mill, many research teams around the world have been working on these problems in order to reduce the cost of transportation through optimal backhauling (Carlsson and Rönnqvist, 2007).

Most models developed to support forest planning do not take the market or prices into account; only at the operational level are these factors considered. Beaudoin et al. (2007a) propose deciding which blocks to harvest in terms of the mills' demand plans and the volume constraints due to forestry imperatives. Since it has an impact on production and inventory costs, freshness is also considered in the model. The harvesting plan obtained maximizes profits by increasing revenues through an efficient wood allocation to the mills and by reducing operating and transportation costs. Prices are set as a function of supply volume and freshness.

PLANS (Twito et al., 1987) was an early equipment and road planning system developed by the US Forest Service, and a similar system was introduced in New Zealand (Cossens, 1992). Both systems are used to simulate harvest area choices, roads to be built to harvest the areas, and the volume of timber that could be harvested. The user proposes the equipment locations, and in a visual, interactive way, the system determines the areas to be harvested by each machine, the roads that need to be built and the timber volumes that can be 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 equipment location decisions. Their system, based on user-GIS interaction and a heuristic for determining good solutions, has been used successfully by forest firms in Chile and Colombia.

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

Carlgren et al. (2006) developed a MIP model that integrates sorting at harvest sectors and transportation. Sorting the logs in the forest leads to higher harvesting and transportation costs, but also provides better quality logs for saw mill production. By improving transportation planning (e.g., by using backhauling), the increased harvesting costs can be reduced.

In many cases, bucking decisions are integrated into the decisions made about which stands to harvest. The number of possible bucking patterns is very high, given the many combinations of lengths and diameters. Different bucking methods have been explored by McGuigan (1984), Eng et al. (1986), Mendoza and Bore (1986), Briggs (1989) and Sessions et al. (1989). Successful applications are reported to have been used in New Zealand (Garcia, 1990) and in Chile (Epstein et al., 1999). Bucking can be carried out at sawmills, where each tree is scanned and analyzed individually, or in-forest by implementing optimizers directly into mechanized harvesters. Marshall (2007) has studied two basic approaches: Buck-to-Value, in which specific prices are assigned to each product, and Buck-to-Order, in which products are harvested to satisfy specific orders. Dynamic Programming and metaheuristics are the main algorithms proposed for such processes, and commercial codes have been developed and are now used by forest firms.

4.1.4 Operational Routing

ASICAM (Weintraub et al., 1996), a DSS for logging trucks, received the Franz Edelman Award in 1998. This DSS is currently used by several forest companies in Chile and other South American countries. It exploits a simulation-based heuristic to produce a one-day schedule. The Swedish system, RuttOpt (Flisberg et al., 2009; Andersson et al., 2007), establishes detailed routes for several days and integrates a GIS with a road database, using a combination of tabu search and an LP model. Testing of this system has shown cost reductions between 5% and 20% compared to manual solutions.

Palmgren et al. (2003, 2004) use a Branch & Price method to solve a formulation based on columns (i.e., routes), with one truck type and a one-day planning horizon. Their route-finding subproblem is based on a variety of heuristics. Murphy (2003) formulated a general integer programming model for the routing problem, but used it only for tactical planning. Gronalt and Hirsch (2005) have described a tabu search method for determining routes given a set of fixed destinations. Their formulation includes time windows and multiple depots for solving small problems involving only one time period.

Dispatching involves determining routes (or partial routes) continuously during the day, taking real time events (e.g., queuing, bad weather, truck breakdowns) into account. Rönnqvist and Ryan (1995) have described a solution method for dispatching, which finds solutions for a fleet of trucks within a few seconds by recursively solving a column-based model whenever data changes occur.

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

Forwarding operations are another type of routing problem. Flisberg and Rönnqvist (2007) have recently proposed a system designed to support forwarding operations at harvest sectors. Using a DSS, this system improves forwarding operations about 10% by establishing better routing. In addition, it produces better information on supply locations and volumes that can be used in subsequent truck transportation planning.

4.1.5 Fire

Fire is one example of a natural disruption that occurs in forests, thus affecting supply chain planning. Fire management processes include both long-term integrated fire and forest management planning and the short-term dispatching of fire crews to stop fire from spreading. Fire management processes can vary from country to country, due to differences in climate, vegetation and societal needs (Martell, 2007). Previous reviews of the literature on the subject (Martell,1982; Martell et al., 1998) underline the fact that fire can have a very significant impact, both in terms of forest management and supply chain planning. For this reason, the subject requires careful examination.

Martell (2007) defines forest fire management as getting the right amount of fire to the right place, at the right time and at the right cost. This definition raises the question of finding the right balance between the beneficial and detrimental impacts of fire on people and forest ecosystems at a reasonable cost to society.

Fires are stochastic processes, which may be caused by humans or nature (e.g., lightning). Significant effort has been dedicated to building good forecasting models, anticipating the number of fires that will occur over certain time periods in a given space. For example, Cunningham and Martell (1973) studied the number of human-caused fires occurring each day, showing a Poisson distribution of the number of fires that could be expected per day in a given region, with variations due to weather. Kourtz and Todd (1992) looked at lightning-caused fires, proposing a number of forecasting models.

Fire prevention and fire detection are two important aspects of fire management. Some forest fire management agencies use fixed towers or lookout points to continuously scrutinize specific forest sectors; others use fire detection patrol aircraft. Designing such fire detection systems raises interesting OR challenges and questions: for example, "How many observation towers are needed, and where should they be located?" or "How many and which type of patrol aircraft should be chartered, and when and where should they be sent?". Mees (1976) used simulation to evaluate potential tower locations. The Canadian Forest Service has developed many strategic and tactical detection system models over the years to address aircraft management issues (Kourtz, 1967; Kourtz, 1971; O'Regan et al., 1975).

Initial attack resource deployment and dispatching are the processes that are launched when a fire occurs. The deployment and dispatching problems are made more difficult by the variations in the fire arrival rates and service times throughout the day, resulting in a similar variation in the resource needs over the day. Martell (2007) has defined the initial attack dispatching problem as 1) the determination of the resources (e.g., fire fighters and air-tankers) that must be dispatched, by ground and/or air, to each reported fire, and 2) the prioritization of the various fires when more than one is burning out of control, deciding which will be attacked first or which will receive the greater part 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 have attracted the attention of practitioners as well as researchers. This can be partially explained by the fact that the industry has typically been driven by a push model in which the main decisions are related to when and where to cut the trees, followed by decisions about processing and selling the resulting products. This section presents a number of interesting contributions to the field.

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

Martel et al. (2005) proposed an OR model for optimizing the structure of multinational pulp and paper production/distribution networks. In their article, the authors identify the main factors that have an international impact on the industry and show how these factors can be taken into account when designing a supply chain. The main factors include national taxation legislation, transfer price regulations, environmental restrictions, trade tariffs and exchange rates. However, adding these features to the planning model considerably increases the complexity of the problem. The authors used a general production/distribution network model dealing with many-to-many processes to illustrate how this kind of problem could be solved. They proposed a large mixed integer program formulation derived from an activity-based model of the supply chain. In their model, harvesting decisions are not optimized, and the fiber supply is a constrained input.

Gunnarsson et al. (2007) have developed a strategic planning model for the Södra Cell kraft pulp supply chain. The main objective of this model is to optimize the assignment of the various products to the different mills. Södra Cell has five pulp mills, three in Sweden and two in Norway, all producing kraft pulp. The entire pulp supply chain is described using an 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 obtained. The user defines whether or not a given contract has to be taken in its entirety or if a part of the contract (with lower bounds) can be chosen. Various modes of transportation can be selected to deliver the pulp to its final destination. Pulp recipes are allowed to vary within a min/max range in terms of the amounts of the different wood varieties used to make different products. This model is used by Södra Cell's managers to evaluate different scenarios of wood availability and cost or to optimize the composition of the product portfolio. In fact, since transition costs are relatively high, a kraft pulp mill suffers significant costs due to having to produce many different products, especially when mixing hardwood and softwood on the same production line.

Gunnarsson et al. (2006) dealt with the strategic design of the distribution network at Södra Cell, which operates three long-term chartered vessels (i.e., ships) for pulp distribution only. The efficiency of the ship routing depends on the terminal structure. With a few large-volume terminals, there is a greater chance that the ships can be unloaded at a single terminal, whereas if there are many small-volume terminals, ships will probably have to stop at two or more terminals to be unloaded. The authors developed a model in which terminal location is combined with ship routing. This is an example of strategic planning, in which it is also important to account for some operational aspects (i.e., ship routing).

Philpott and Everett (2001) presented their Fletcher Challenge work, which was to develop a model (PIVOT) for optimizing 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 were added to model specific mill conditions, such as the 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 Fletcher Challenge management team.

Everett et al. (2000) proposed the SOCRATES model, 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 are the introduction of capital constraints and the use of a multi-period planning horizon. This model was further developed in the COMPASS model (Everett et al., 2001), implemented in three Norske Skog mills in Australia and New Zealand. The objective function was modified to account for taxation in the two countries, and a feature was added to allow the paper recipe to vary in terms of the wood pulps used, depending on capital investment decisions. The intention was to evaluate the possibilities of using a less costly recipe based on the capital investments for the paper machine.

A crucial part of the supply chain is the procurement of appropriate wood fibers for the different final products that may be produced. Wood is normally sorted into different assortments with specific properties. However, creating more assortments for the sorted wood is costly and generally a single party cannot independently make the decision to create more assortments. Weigel et al. (2005) presented a model optimizing wood sourcing decisions, including wood sorting strategies as well as technology investments, in order to maximize the profit of the supply chain. The model's objective is to maximize the supply chain's contribution margin (i.e., the sales revenues minus diverse fixed and variable costs). The model assumes that the wood available in aggregated supplies can be sorted in different ways representing distinct grades. Each pulp and paper product can be made according to a set of viable recipes involving different proportions of the various wood grades. In the article, the authors used a test case to show that a substantial improvement of the objective value can be achieved by optimally allocating fiber types to the right process stream, while at the same time optimizing the supply chain output with respect to the different end-products.

Interesting models have also been developed to support tactical planning in the pulp and paper industry. For example, Bredström et al. (2004) developed one for the Swedish pulp producer, Södra Cell. This model can be used to plan with respect to individual wood sources, mills and even aggregate demand zones or to produce individual production schedules for the mills. Compared to manual planning, the optimized schedules reduce the global storage and logistics costs, despite an increasing number of changeovers.

Bouchriha et al. (2007) developed a model for production planning in a context of fixed-duration production campaigns. The objective of the study was to fix the campaign duration on a single paper machine at a North American fine paper mill. This planning model can be used to anticipate the cost of planning for a variety of different fixed-duration production campaigns, despite possible inter-cycle variations in the volume of each product produced. The difficulty in resolving this problem is caused 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. Subsequently, the sheeting is done as customer orders are received. The authors propose a model for determining the best assortment of parent rolls to keep in stock in order to minimize the expected inventory holding and trim loss costs. When tested on real data from one of the largest fine paper mills in North America, the model was able to reduce inventory holding costs substantially, while at the same time achieving a slight reduction in trim loss costs.

At the operational level, Rizk et al. (2006) have presented a model for planning the production on multiple machines in a single mill. The production planning is integrated with the distribution planning for a single distribution center, and 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 conversion to final products. Economies of scale in transportation are accounted for through a piecewise linear function. The results for a real case involving one of the largest uncoated free-sheet producers in North America show considerable savings when production and distribution decisions are optimized all together, as compared to optimizing distribution planning first, and then optimizing the production planning. In a subsequent article (Rizk et al., 2008), the previous model was expanded to include multiple distribution centers.

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

Bredström et al. (2005) dealt with operational planning for pulp distribution. Their model focuses on routing and scheduling ships, in coordination with other available means of transportation, such as truck and rail.

Bergman et al. (2002) studied roll cutting in paper mills. Roll cutting is a well-known academic problem for which efficient solution methods exist. However, in an industrial setting, there are many practical issues to consider, such as a limited number of knives in the winder, products that must (or must not) be cut in the same pattern, different product due dates, or limited inventory space. Another practical issue is that, given a minimum number of rolls, the objective is to use as few cutting patterns as possible in order to limit setup costs and times. This article describes a system that takes these issues into account and provides the results of tests with a set of case studies. Other roll cutting models particularly suited for the paper industry have been presented by Goulimis (1990) and by Sweeney and Haessler (1990).

Finally, Flisberg et al. (2002) described an online control system for the bleaching process in a paper mill. The problem involves determining the number of chemical charges in various bleaching steps. The objective of the system is to help operators minimize chemical use, thus reducing the cost of chemicals, and improve the pulp brightness (over time) before it reaches the paper machines.

4.3 Lumber, Panel and Engineered Wood

The work of Vila et al. (2006, 2007), who have proposed a generic method for designing international production/distribution networks for make-to-stock products with divergent manufacturing processes, has been applied in the lumber industry. In their papers, these authors have addressed the lumber industry's strategic planning decisions under stochastic demand conditions and prices. The objective of this method is to design a supply chain, including the opening/closing of mills, technology investments and market decisions (e.g., product substitution), that will position the company favorably in order to earn anticipated high-value market shares. Three different sub-markets are considered in the model: contract markets, vendor-managed inventory markets and spot markets. Vila et al. (2007) formulated the production/distribution network design problem 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, with the forestry decisions being made externally and modeled as supply constraints in the model.

For secondary wood products, Farrell and Maness (2005) used a relational database approach to create a decision support system based on integrated linear programming. This generic DSS, used to analyze short-term production planning issues, is able to evaluate production strategies in the highly dynamic environment typical in a wide variety of secondary wood product manufacturing plants.

For timber and lumber products, Maness and Adams (1993) proposed a mixed integer program model integrating the bucking and sawing processes. Formulated as a mixed integer program, this model accounts for inelastic demand by controlling price–volume relationships, while linking log bucking and log sawing for a specific sawmill configuration. The system developed can handle the raw material distribution of one sawmill over one planning period for a deterministic final product demand. Maness and Norton (2002) later proposed an extension to this model capable of handling several planning periods.

Reinders (1993) developed a decision support system for the strategic, tactical and operational planning of one sawmill, where the bucking and sawing operations are done in the same business unit. This model does not take into account other processes, such as 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) and Forget et al. (2007) have all proposed an agent-based experimental platform for modeling different lumber supply chain configurations (i.e., many mills and generic customer/supplier relations). This model represents the sawmilling processes as alternative one-to-many processes constrained by bottleneck capacity. The drying processes are also represented as one-to-many processes, in which green lumber is divided into groups according to specific rules, and extended drying programs, including air drying, are considered. Like the first two processes, the finishing processes are modeled as one-to-many processes, but this time, with setup constraints.

The authors (see previous paragraph) used different business cases to validate the system and the specific planning models proposed (e.g., linear programming, constraints programming and heuristics). An industrial implementation was conducted to test the platform's scaling capacity. In addition, simulations were done to evaluate different strategies for the lumber industry, given different business contexts. The simulator was able to deal with many sawmills, drying and finishing facilities. During the simulation, wood procurement was set as a constraint, and demand patterns were stochastically generated according to different spot market and contract-based customer behaviors. To help planners make strategic and tactical decisions, the platform simulates the supply chain at the operational level, planning the procurement, production and distribution operations to be conducted during every shift or day in the planning horizon.

Tactical planning in the lumber, panel and engineered wood products industries has also been discussed in the literature. Such contributions illustrate the challenge of integrating the different business units in the lumber supply chain (Lidén and Rönnqvist, 2000; Singer and Donoso, 2007), in 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) introduced CustOpt, an integrated optimization system allowing a wood supply chain to satisfy customer demands at minimum cost. The model includes the bucking, sawing, drying, planing, and grading processes. This integrated system, which is a tactical decision support tool with a 3-month planning horizon, was tested in conditions involving two to five harvesting districts, two sawmills and two planing mills.

From a similar perspective, Singer and Donoso (2007) recently presented a model for optimizing planning decisions in the sawmill industry. They modeled a supply chain composed of many sawmills and drying facilities, with storage capacities available after each process. In this problem, each sawmill is considered as an independent company, making it imperative to share both the profitable and unprofitable orders as equitably as possible. The model allows transfers, externalizations, production swaps and other collaborative arrangements. The proposed model was applied at AASA, a Chilean corporation with 11 sawmills. Based on the results of the testing, the authors recommend using transfers, despite the explicit transportation costs incurred. They also recommended that some plants focus almost exclusively on the upstream production stages, leaving the final stages to other plants.

Ouhimmou et al. (2007) recently presented a MIP model for planning the wood supply for furniture assembly mills. Their model addresses multi-site and multi-period planning for procurement, sawing, drying, and transportation operations. Assuming a known demand that is dynamic over a certain planning horizon, the model was solved optimally using CPLEX and approximately using time decomposition heuristics. The model was then applied to an industrial case with a high cost-reduction potential, with the objective of obtaining procurement contracts, setting inventory targets for the entire year for all products in all mills, and establishing mill-to-mill relations, outsourcing contracts and sawing policies.

Feng et al. (2008) applied the concept of sales and operations planning (S&OP) to supply chain planning. They use sales decisions to investigate the opportunities of profitably matching and satisfying the demands of a given supply chain, given the chain's production, distribution, and procurement capabilities. More precisely, they proposed a series of mathematical programming models to evaluate the benefits of choosing integrated S&OP planning over the traditional decoupled planning process in the context of a real OSB manufacturing supply chain system within a make-to-order environment. The integrated S&OP planning process demonstrated a greater benefit when facing increased procurement costs or decreased market prices for final products, suggesting that difficult economical conditions call for integrated planning.

At the operational level, the cutting problem is often critical. Whether dealing with timber, hardwood or softwood lumber, paper, panels or engineered wood products, optimal cutting of incoming products is crucial in terms of material yield management as well as demand satisfaction. The general literature provides many models that deal with cutting problems. In the forest products industry, difficulties stemming from wood defects and wood grading must be considered, raising the need to tackle difficult 2D or even 3D problems. One example dealing with such complex problems is the Todoroki and Rönnqvist study (2002), which attempted to find the optimal cutting pattern for dimension parts from *Pinus Radiata*. Clearly, given the typically high production rates in the forest products industry, the different cutting problems must be solved rapidly.

In the furniture industry, many studies have attempted to optimize the cutting list at the mill level in order to meet demands and minimize wood loss (Buelmann et al., 1998; Carnieri et al., 1993; Hoff, 1997). The cutting lists define how the dimension parts should be grouped together so the associated cutting processes can be performed using as few wooden boards as possible.

4.4 Heating

To provide heat energy, an increasing number of heating plants are being implemented. Gunnarsson et al. (2004) presented a planning model for such plants, which are normally operated by local communities. To insure their fuel supply, the heating plants award contracts to one or several entrepreneurs through a competitive bidding process. 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 that can be used in the heating plants exist, and one important type is forest fuel. Forest fuel can be chipped forest residues (i.e., residues converted into small pieces), sawmill byproducts (e.g., sawdust), or wood without any other industrial use. Forest residues include the branches and tree tops that are left in harvest areas after the logs have been transported to sawmills or pulp mills. Once the residue is dry, it is forwarded and piled in the harvest sector. It can be chipped directly in the harvest sector using mobile chippers, or transported to terminals or heating plants where it will be chipped at some stage with a fixed or mobile chipper. Transportation constitutes a large proportion of the overall handling costs, and there is obviously a trade-off between chipping directly in the harvest areas or waiting to chip at the terminals. It is typically cheaper to chip at terminals, but transporting non-chipped forest residue is more expensive than transporting wood chips. With the increased price of energy, trade in emission rights and different tax systems, the use of pulp logs directly at heating plants has increased. The competition between pulp and paper producers and heating plants is expected to grow in the future.

5. COLLABORATIONS IN THE FOREST PRODUCTS INDUSTRY

Collaboration issues are tightly linked to any discussion of supply chains. However, it is only recently that OR has been used to evaluate the potential of collaboration for the forest products industry. This recent interest in OR has raised thought-provoking research questions. The following articles show how the value of collaboration in the forest products industry has been addressed recently in the OR literature.

Given that many companies obtain their wood allocations from unevenly aged forests owned by the state, they often need to agree on a common in-forest harvesting plan. Beaudoin et al. (2007b) addressed this problem proposing collaborative approaches to help the negotiation process converge on a profitable balanced solution. In their article, they first propose a planning approach to help each company establish its own optimal plan for several different scenarios. Then, they illustrate the value of collaboration for determining a final harvesting schedule.

The benefits of collaboration have also been explored in the context of transporting logs to mills. Often, many companies operate in different parts of the country, which provides opportunities for optimizing backhauling operations. This opportunity has been addressed in different parts of the world, using the specific wood allocation and trucking constraints found in each region. Frisk et al. (2006b) (Sweden), Palander and Vaatainen (2005) (Finland), and Audy et al. (2007) (Canada) have all worked on different versions of this problem. They have also proposed models for sharing risks and benefits.

Finally, collaboration between paper mills and customers has been explored by Lehoux et al. (2007). Four different approaches to integration were simulated and optimized, starting with the traditional make-to-order, then moving toward continuous replenishment, vendor-managed inventory (VMI) and finally Collaborative Planning Forecasting and

Replenishment (CPFR). Of all the tested scenarios, CPFR showed the greatest overall benefit. However, under certain economic conditions, customers may obtain a greater benefit from a continuous replenishment approach, while producers still obtain a greater benefit from the CPFR approach.

6. CONCLUSION

This paper has presented a description of the wood fiber flow from forest to customer, providing details about the major supply chains of the forest products 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 was first discussed in general terms and then more specifically for each of the individual supply chains.

A non-exhaustive review of literature was presented in order to illustrate the major planning problems in the forest products industry. The review showed that very little work has been done to link the forest supply chain to the other forest products supply chains. The integration of the various supply chains is still a major challenge for the industry, and researchers should work to develop new models to support such integration.

Operational Research has played an important role in supporting forest products industry managers and public officials in their planning decisions. Canadian researchers have been contributing to the many different aspects of this field for many years. The cultural and historical backgrounds of many Canadians, in addition to the importance of this industry for Canada, have motivated them to develop models and tools to deal with forest management, forest road building, harvesting, fire management, transportation and different supply chain planning problems of the forest products industry. This paper recognizes their contributions in the context of the 50th anniversary of the Canadian Operational Research Society.

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