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# Tactical supply chain planning in the forest products industry

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## Abstract

This paper presents a mixed integer programming model which aims at supporting wood procurement tactical decisions of a multi-facility company. This model allows for wood exchange between companies. Furthermore, the material flow through the supply chain is driven by both a demand to satisfy (Pull strategy) and a market mechanism (Push strategy), enabling the planner to take into consideration both wood freshness and the notion of quality linked to the age of harvested wood into demand. The incapacity to consider alternative plans for implementation, and the difficulty to assess the performance of these plans in an uncertain environment are two shortcomings of the manual planning process. Thus, a planning process, based on human – decision support system interactions, allowing overcoming these shortcomings is presented. The process combines Monte Carlo methods and an anticipation mechanism permitting to take into account equipment transportation costs. The proposed planning process results into a multi-criteria decision making problem where the human planner has to select a plan to implement from a set of candidate plans. A test case shows that it is possible to manage the wood flow from the stump to end market in a way to preserve its freshness and to extract higher value from the logs processed in the mills. Results also show that the proposed planning process achieves an average profitability increase of 8.8%, as compared to an approach based on a deterministic model using average parameter values.

# Introduction

Wood procurement planning is a complex task as a multitude of factors must be taken into consideration. It is even more complex in a multi-firm environment, where firms may supply each other, and where forest stands are composed of several tree species. Yet, planning is still largely done based on intuition and without mathematical programming support. The main problem associated with this process is the time spent collecting and verifying data, which leaves little time for the actual planning and interactions with industrial and recreational users. Furthermore, the considerable amount of time required to build a single plan prohibits the evaluation of alternative plans.

The contributions of this paper are (1) a detailed tactical model to support the centralized annual planning of an integrated forest company which may include many mills and allows for wood exchange between companies; (2) an extension of the market mechanism presented in Maness (1989) in order to model market needs taking wood freshness into consideration; (3) a planning process for the generation and evaluation of candidate plans.

The remainder of this paper is organized as follows. A literature review is presented in the next section, followed by the problem description. The planning process is then introduced with its different components. Then, the mathematical formulation of the tactical wood procurement model is described. Follow a test case description, the results and concluding remarks.

# Literature review

### Models

The use of mathematical models to deal with wood procurement problems can be traced back to the early 1960s. Since then, a large body of models has been developed to address different aspects of wood procurement. Some have been designed for specific activities such as skidding

(Carlsson *et al.* 1998) or transport decisions (Wightman and Jordan 1990, Weintraub *et al.* 1996). Others have integrated several activities within a single model in order to capture possible synergies between individual activities. For instance, Burger and Jamnick (1995) have integrated harvest, storage and transport decisions, while Karlsson *et al.* (2004) include allocation of harvest teams in addition to these questions. To our knowledge, no attempt has been made to address these decisions taking into account mills' production decision anticipation, even though significant gains could be achieved due to higher fiber freshness (elapsed time between harvesting and processing at the mill).

### Deteriorating items

In the last decade, the industry has come to realize the importance of being procured with fresh fibers. Common problems associated with log storage are checks development due to drying and sapstain. Even if sapstain does not change the structural wood integrity, it can severely damage the appearance of wood, resulting in serious loss of value (Kreber *et al.* 2001). Laganière and Defo (2002) have looked at the impact of timber freshness for sawmill operators. They have identified problems associated with the log yard, debarking, sawing, drying, planing and grading. They concluded that for all activities, an older fiber is detrimental to a sawmill's performance. Similarly, Bico (2002) and Wood (2002) discussed the impact of storage duration on pulp yield, pulp brightness and processing costs of pulp mills.

Production planning and scheduling of deteriorating items has long been the subject of articles, but such considerations have appeared only recently in models dealing with the harvest and distribution planning problem. Karlsson *et al.* (2002) were among the first to introduce age related storing costs. In their model, fiber deterioration is taken into account by associating a value reduction to an assortment with regard to the age of the harvested timber. Two improvements can be made to this approach. First, the value reduction does not take into consideration the seasonal variation in the rate of deterioration of the fibers. It is not only the time elapsed between the moment a tree is harvested and the moment it is transformed into diverse products that should be considered, but also the periods or seasons over which the elapsed time occurs. Second, their model considers the rate of deterioration to be the same regardless of the storage location and the end products to be manufactured. Storage locations are sometimes far apart, and even if the seasonal rate of deterioration is the same, the beginning of a season may differ over the land base. Furthermore, mills may use different technologies and may not be affected in the same way by the freshness of the resource. The formulation proposed in this paper accounts for these considerations.

## Uncertainty

Forest managers and researchers are increasingly concerned with uncertainty and would like to account for it when making decisions. Weintraub and Bare (1996) and Martell *et al.* (1998) identify wood procurement planning under uncertainty as a new challenge for researchers. To date, the majority of models tackling the wood procurement problem have focused on deterministic formulations of the problem. A fundamental property of deterministic models is that all required data are supposed to be known with certainty. This is an important assumption that limits the validity of any linear programming solution to a supply chain problem (Shapiro 2001). The main criticism of these applications is not necessarily the use of deterministic decision models in nondeterministic environments but rather the lack of focus on the analysis and validation of the so called optimal solution. Contingency analysis is a necessary step before any decision should be made.

Relatively few researches considering stochastic conditions in wood procurement problems have been undertaken. For a review of stochastic parameters and approaches adopted to take uncertainty into consideration, we refer the reader to Weintraub and Bare (1996) and Martell *et al.* (1998). The most commonly used methodologies are sensitivity analysis and scenario-based analysis. Sensitivity analysis consists in varying the value of a parameter to find the extent to which the change affects the results of the outcome, while scenario-based analysis is a process of analyzing possible future events by considering alternative possible outcomes. Major drawbacks of these two methods are their incapacity to evaluate the impact of the interactions between the various stochastic parameters and the lack of knowledge concerning the probability of occurrence of each scenario. An adaptation of the two-stage stochastic decomposition method presented in Goetschalckx *et al.* (2001) permits to overcome these shortcomings.

# Problem description

The problem we consider is one where most of the productive forested land is within the public domain. This land base is divided into procurement areas. Government allocates volumes of timber to mills through timber licenses (TL). A TL is awarded to each mill, regardless of their ownership. A TL specifies, on a yearly basis, the procurement areas from which the mill can be procured with predefined volumes of one or more resource types (tree species). A mill may hold TL on more than one procurement area, and several TL may be awarded to different mills on the same procurement area, even for the same tree species. Sharing a procurement area means that in a single block, harvested volumes are sorted according to their characteristics and their ability to be manufactured into certain product types (for example: softwood lumber, hardwood lumber, pulp and veneer) in order to be delivered to the appropriate mills. Furthermore, even if most companies manage their own operations, part of their needs for raw materials must be fulfilled through the purchasing of logs from other companies' operations due to the mixed nature of stands. These relationships are characterized by pooled-type dependencies, also called resource sharing dependency (Frayret *et al.*, 2004), and must be managed by coordinating procurement activities. In order to procure its mills, a company must coordinate its operations on several procurement areas and with those of other companies.

The problem at hand is to maximize a firm's profit while satisfying demands for end products and wood chips covered under agreements or contracts, and demand for logs from other companies. The model proposed hereafter takes into account volume restrictions for the origin of the wood over the land base and the deterioration of fibers which affects the net revenue obtained from the sales of end products.

The developed model addresses the tactical wood procurement planning problem. We assume that a strategic planning has been previously executed. The output of this process corresponds to a 5 year development plan which identifies blocks to be harvested in each of the year covered by the plan. The annual plan brings more details surrounding the activities on blocks identified for harvesting in the first year of the 5 year development plan. Volumes for each resource on every block are assumed to be known. A resource is defined by type and quality as defined by the government to determine stumpage fees. It is to be noted that for a same resource, stumpage fee is fixed over a tariff zone but variable from one zone to another. A procurement area may cover more than one tariff zone.

### Market anticipation functions

The objective of minimizing procurement cost while satisfying mills' demand is adequate from a supplier point of view. However, in an integrated wood production system it seems to be short sighted. As outlined by Gingras and Sotomayor (1992), increased procurement costs could be acceptable and justifiable to preserve fiber quality as long as the incurred cost is offset by a reduction in processing costs at the mill or in a gain of revenue from the sales of products and by-products. Therefore, our model attempts to integrate harvesting decisions along with the anticipation of log distribution and mills' aggregated production planning. Because only part of a mill's production capacity is covered by long term contracts with customers, the use of the excess capacity must be planned in order to provide end products to the open market. The market mechanism presented by Maness (1989) has been adapted to take into consideration fiber freshness and is illustrated in Figure 1.

**INSERT FIGURE 1**

Market anticipation functions are used to estimate what aggregated levels of production at the mills are the most profitable in order to guide the upstream operations. Such function uses valuation levels. A valuation level represents the average unit revenue from the sale of a particular end product made from a given resource, net of their average processing cost. It is constrained by a maximum number of units that can be sold at that valuation level. Decreasing value from a level to another within an age class represents the increased uncertainty associated with the unit revenue from the sale of end products. Age classes are bounded by a lower and an upper value and do not have to be of homogeneous length. Levels of valuations are defined for each age class. Variation over age classes reflects the quality of end products. The older the fiber used, the lower the expected profit margin on that end product. Deterioration of wood fiber is thus taken into account through a value reduction.

Yang *et al.* (1999 and 2001) indicate that the severity of deterioration may vary with season, tree species, local environment, and storage conditions. Thus a market anticipation function is required for each resource in every season in order to take into consideration the seasonality of the deterioration rate and of end product market price. Moreover, every mill may have its own market anticipation functions due to different end products being manufactured or different technology being used.

## Planning process

Among the shortcomings of a manual planning process, there is first the incapacity to consider alternative plans for implementation and also the difficulty to assess the performance of the plans in a stochastic environment. The proposed planning process (Figure 2) is an adaptation and an extension of the two-stage stochastic decomposition method developed and presented in Goetschalckx *et al.* (2001) and permits to overcome both of these shortcomings.

**INSERT FIGURE 2**

The mathematical deterministic model presented hereafter does not address robustness explicitly. Rather, the proposed planning process makes use of a set of mechanisms to assess *a posteriori* how several alternative plans meet some key objectives. The proposed planning process starts by creating scenarios by randomly generating values for the uncertain parameters for each period considered in the model based on their given probability distributions. For each scenario the optimal plan (referred to as the candidate plan) is determined by solving a deterministic mixed integer program. Each candidate plan is then submitted to further analysis: 1) Each candidate plan is submitted to the harvest block sequencing and equipment transportation model in order to evaluate the operational equipment transportation cost of the plan; and 2) Each candidate plan is simulated using different scenarios. In each of these analyses, statistics are gathered in order to help the planner resolve the resulting multi-criteria decision problem.

### Scenario generator

Uncertainty is inherently present in a wood procurement network. Scenarios are generated using a Monte Carlo method. It is useful for evaluating interdependencies among random effects that may cause serious degradation in performance even though the average performance characteristics of the system's components appear to be acceptable (Shapiro 2001). The Monte Carlo method uses probability distribution functions of key factors of uncertainty in the supply chain in order to randomly generate numbers.

### Deterministic wood procurement planning model

For each scenario, a deterministic mixed integer program is used to find the optimal plan. For each scenario corresponds an optimal plan (i.e., the candidate plan). In this model (see next section), due to block sizes, which range from a few hectares to over 100 ha, and the desire to reduce inventories, preemption is allowed in regard to harvesting (i.e. a block does not have to be harvested all at once).

### Harvest block sequencing and equipment transportation model

Due to the highly combinatorial nature of the block sequencing problem, equipment transportation cost is not included in the tactical model. Instead, this cost is taken into account by anticipating for each candidate plan the output of an operational model of the sequencing problem. The purpose of this model is to minimize a firm's equipment transportation cost while harvesting targeted volumes identified per period in the candidate plans. The model aims at identifying an operational plan while taking into account equipment capacity which restrict the time spent to harvest and to move from one block to another. It is designed to address particularly the harvest block sequencing and equipment transportation problem. For more details about this aspect of the planning process, the reader is referred to Beaudoin *et al.* (2005).

### Rule-based simulation

The rule-based simulation aims at assessing how a given plan unfolds if different scenarios occur. Instead of randomly generating new scenarios to evaluate each candidate plan, we used those previously generated, as suggested by Novak & Ragsdale (2003). In their work, these authors reformulate the problem before re-evaluating candidate solutions under alternate scenarios. This reformulation is necessary so as to avoid violating the flow conservation constraints. To avoid this reformulation, we use a rule-based simulation approach.

More specifically, rules are defined in terms of IF-THEN. These rules adjust the values of output variables in order to respect the capacities and other parameters of the scenarios. For example, let us say the plan under consideration identify a target of 500 $m^3$ to be harvested on a specific block, but under the current scenario that block only holds 450 $m^3$. The harvest variable for that block is then adjusted downward in order to respect the capacity of the block. In the case where there is no breach in capacity, no adjustment is required. The same rule also applies for transportation, storing and milling variables of the candidate plan. Since activities along supply chains are highly dependent, flow balancing adjustments are also required to reflect previous adjustments.

### Decision making

Finally, different metrics are calculated and gathered in order to assess each plan and to support decision making. These metrics include the average and standard deviation of profit, the equipment transportation cost, the volumes to be acquired from private woodlot owners, and the feasibility of a plan. Volumes to be acquired from private woodlot owners correspond to missing volumes of resources needed to satisfy demand for end products and wood chips. Meanwhile, if demand for logs from other companies cannot be fulfilled by the company’s operations according to the terms agreed upon, then the plan is deemed infeasible. This indicator captures the risk associated to a plan due to the propagation of the stochastic effects throughout the network of interdependent companies. It is to be noted that the metrics used for decision making are not restricted to the ones presented here. Any metrics representing the preferences of the decision maker could be accommodated for through the proposed planning process and its constituents.

The proposed planning process thus provides insights into the system's performance, something that cannot be obtained by deterministic optimization models used on their own. The planner then faces a multi-criteria decision problem to select a candidate plan for implementation. Here, the process is applied to plans generated with a deterministic optimization model. It is to be noted that it can also be applied to plans generated intuitively by the planner or strictly based, for example, on its experience.

# Mathematical formulation

In this section the mathematical model of a firm's centralized tactical wood procurement planning is presented. Data sets are first introduced, followed by the parameters and variables used to formulate the model. Finally the model formulation is described.

**Sets**

$A$: Set of possible ages of the harvested timber.

$C$: Set of age classes.

$E$: Set of other firms.

$I$: Set of harvesting blocks within the procurement areas covered under the timber license of the mills under the company's ownership.

$K$: Set of procurement areas.

$N$: Set of valuation levels.

$R$ : Set of forest resources.

$S$ : Set of forest resource types.

$T$ : Number of periods.

$U$ : Set of mills under the company's ownership.

$U'$ : Set of mills under other ownership.

$K_{(u)}$ : Set of procurement areas covered under the timber license of mill $u$.

$I_{(k)}$ : Set of blocks within procurement area k.

$I_{(Ku)}$ : The set of blocks within the procurement areas covered under the timber license of mill $u$, *for* $u \in U$ or $u \in U'$.

$R_{(s)}$ : Set of resources with the same tree species.

$R_{(u)}$ : Set of resources desirable for mill $u$, *for* $u \in U$ or $u \in U'$.

A resource is said to be desirable or usable by a mill when it is entitled to that resource type according to its timber license and it is of an acceptable quality in regard to the end product it will be transformed into.

In the remainder of this paper, index $a$ will be used for ages of harvested timber, $c$ for age classes, $e$ for firms, $i$ for blocks, $k$ for procurement areas, $n$ for valuation levels, $r$ for resources, $s$ for resource type, $t$ for periods, $u$ for own mills, and $u'$ for other's mills.

**Parameters**

$a_c^-$ and $a_c^+$ : Lower and upper age of age class $c$ respectively.

$a_c^+$ : Upper age of age class $c$.

$b_t^H$ : Total harvesting capacity in period $t$.

$b_t^T$ : Total transportation capacity in period $t$.

$b_{ut}^S$ : Total storing capacity at mill $u$ during period $t$.

$b_{ut}^{P}$: Total processing capacity of mill $u$ during period $t$.

$b_{rut}^{\min}$: Minimum volume of resource $r$ stored at mill $u$ during period $t$.

$c_{it}^{H}$: Unit cost to harvest block $i$ during period $t$.

$c_{rit}^{S}$: Unit cost to store resource $r$ on block $i$ during period $t$.

$c_{rut}^{S}$: Unit cost to store resource $r$ at mill $u$ during period $t$.

$c_{riut}^{T}$: Unit cost to transport resource $r$ from block $i$ to mill $u$ during period $t$.

$c_{riu't}^{T}$: Unit cost to transport resource $r$ from block $i$ to mill $u'$ during period $t$.

$d_{sa_u^{\max}ut}^{chips}$: Demand for chips of resource type $s$ of a maximum age $a_u^{\max}$ at mill $u$ during period $t$.

$d_{ra_u^{\max}ut}^{endproduct}$: Demand for end products made from resource $r$ of a maximum age of $a_u^{\max}$ at mill $u$ during period $t$.

$d_{ra_{u'}^{\max}u't}^{\log}$: Demand for logs of resource $r$ of a maximum age $a_u^{\max}$ at mill $u'$ during period $t$.

$f_{rit}$: Stumpage fee for resource $r$ on block $i$ during period $t$.

$g_{sut}^{chips}$: Unit revenue from the sale of chips of resource type $s$ at mill $u$ during period $t$.

$g_{rucnt}^{market}$: Average unit revenue, from the sale of excess production net of processing cost, for end products made from resource $r$ within age class $c$ at mill $u$ and sold at valuation level $n$ on the open market during period $t$

$I_{rai0}^{F}$: Volume of resource $r$ of age $a$ stored on block $i$ at the beginning of the planning horizon.

$I_{rau0}^{U}$: Volume of resource $r$ of age $a$ stored at mill $u$ at the beginning of the planning horizon.

$l_i$: Maximum number of periods over which harvesting can occur in block $i$.

$n_t$: Maximum number of blocks in which harvesting can occur during period $t$.

$v_{ri}$ : Volume of resource *r* available on block *i*.

$v_{suk}$ : Maximum volume of resource type *s* that can be delivered to mill *u* from procurement area *k*.

$v_{rucnt}^{\max}$ : Maximum volume of resource *r* within age class *c* that can be transformed and sold by mill *u* at valuation level *n* during period *t*.

$w_{raekut}$ : Volume of resource *r* of age *a* delivered from procurement area *k* to mill *u* by firm *e* during period *t*.

$\alpha_{rau}$ : End products' average yield from processing resource *r* of age *a* through mill *u*.

$\gamma_{rau}$ : Chips average yield from processing resource *r* of age *a* through mill *u*.

**Decision variables**

Decisional variables and their relations with one another are summarized in Figure 3. It illustrates the centralized planning problem as seen from a firm's perspective.

**INSERT FIGURE 3**

Decision variables are divided into two distinct categories: primary decision variables and anticipated or secondary decision variables. Primary decision variables are those for which the planner is responsible of instantiating. Anticipated decision variables are needed in order to coordinate tactical decisions with operational decisions that will eventually be taken to operationalize the tactical plan. In other words, these secondary decision variables only represent an aggregated anticipation of operational decisions for which the considered planner is not directly responsible of.

*Primary decision variables*

$X_{it}$ : Proportion of block *i* harvested during period *t*.

$I^{F}_{rait}$ : Volume of resource *r* of age *a* stored on block *i* at the end of period *t*.

$I^{U}_{raut}$ : Volume of resource *r* of age *a* stored at mill *u* at the end of period *t*.

$H_{it}$ : $\begin{cases} 1, \text{ if harvesting occurs on block } i \text{ during time period } t \\ 0, \text{ otherwise} \end{cases}$

*Anticipated decision variables*

$S_{raiu't}$ : Volume of resource *r* of age *a* transported from block *i* to mill *u'* during period *t*.

$Y_{raiut}$ : Volume of resource *r* of age *a* transported from block *i* to mill *u* during period *t*.

$D_{raunt}$ : Volume of end product made from resource *r* of age *a* that is sold by mill *u* at valuation level *n* on the open market during period *t*.

$M_{raut}$ : Volume of resource *r* of age *a* processed through mill *u* during period *t*.

All variables defined so far, but one, are continuous variables. They can be interpreted as network flow variables in a multi-commodity network describing the possible flows from harvesting blocks to the mills and through a milling process to supply different potential markets.

**Model**

Maximize:

[1]

$$\begin{aligned}
&\sum_{r\in R_{(u)}}\sum_{u\in U}\sum_{c\in C}\sum_{n\in N}\sum_{t\in T}\left(g^{market}_{rucnt}\sum_{a_c^-}^{a_c^+} D_{raunt}\right) + \sum_{s\in S}\sum_{u\in U}\sum_{t\in T}\left(g^{chips}_{sut}\sum_{r\in R_{(s)}}\sum_{a\in A}\left(\gamma_{rau} M_{raut}\right)\right) \\
&- \sum_{i\in I}\sum_{t\in T}\left(c^{H}_{it} X_{it}\sum_{r\in R} v_{ri}\right) - \sum_{r\in R}\sum_{i\in I}\sum_{t\in T} v_{ri} f_{rit} X_{it} \\
&- \sum_{r\in R_{(u)}}\sum_{i\in I}\sum_{u\in U}\sum_{t\in T}\left(c^{T}_{riut}\sum_{a\in A} Y_{raiut}\right) - \sum_{r\in R_{(u')}}\sum_{i\in I\cap I_{(Ku')}}\sum_{u'\in U'}\sum_{t\in T}\left(c^{T}_{riu't}\sum_{a\in A} S_{raiu't}\right) \\
&- \sum_{r\in R}\sum_{i\in I}\sum_{t\in T}\left(c^{S}_{rit}\sum_{a\in A} I^{F}_{rait}\right) - \sum_{r\in R_{(u)}}\sum_{u\in U}\sum_{t\in T}\left(c^{S}_{rut}\sum_{a\in A} I^{U}_{raut}\right)
\end{aligned}$$

Subject To:

[2] $$\sum_{t \in T} X_{it} \le 1, \quad \forall i \in I$$

[3] $$X_{it} \le H_{it}, \quad \forall i \in I, \forall t \in T$$

[4] $$\sum_{t \in T} H_{it} \le l_i, \quad \forall i \in I$$

[5] $$\sum_{i \in I} H_{it} \le n_t, \quad \forall t \in T$$

[6] $$\sum_{r \in R_{(u)} \cap R_{(s)}} \sum_{a \in A} \sum_{i \in I_{(k)}} \sum_{t \in T} Y_{raiut} + \sum_{r \in R_{(u)} \cap R_{(s)}} \sum_{a \in A} \sum_{e \in E} \sum_{t \in T} w_{raekut} \le v_{suk} \quad \forall s \in S, \forall u \in U, \forall k \in K_{(u)} \ ts$$

[7] $$\sum_{i \in I} \left( X_{it} \sum_{r \in R} v_{ri} \right) \le b_t^H \quad \forall t \in T$$

[8] $$\sum_{r \in R_{(u)}} \sum_{a \in A} \sum_{i \in I_{(Ku)}} \sum_{u \in U} Y_{raiut} + \sum_{r \in R_{(u')}} \sum_{a \in A} \sum_{i \in I_{(Ku')}} \sum_{u' \in U} S_{raiu't} \le b_t^T \quad \forall t \in T$$

[9] $$\sum_{r \in R_{(u)}} \sum_{a \in A} M_{raut} \le b_{ut}^P \quad \forall u \in U, \forall t \in T$$

$$I_{rait}^F = \begin{cases} v_{ri} X_{it} - \sum_{u \in U} Y_{raiut} - \sum_{u' \in U'} S_{raiu't} \quad \forall r \in R, \forall i \in I, \forall t \in T, a = 1 & [10.1] \\ I_{r(a-1)i(t-1)}^F - \sum_{u \in U} Y_{raiut} - \sum_{u' \in U'} S_{raiu't} \quad \forall r \in R, \forall i \in I, \forall t \in T, \forall a \ge 2 & [10.2] \\ I_{rai0}^F - \sum_{u \in U} Y_{raiut} - \sum_{u' \in U'} S_{raiu't} \quad \forall r \in R, \forall i \in I, t = 1, \forall a \ge 2 & [10.3] \end{cases}$$

$$I_{raut}^U = \begin{cases} \sum_{i \in I_{(Ku)}} Y_{raiut} + \sum_{e \in E} \sum_{k \in K_{(u)}} w_{raekut} - M_{raut} \quad \forall r \in R_{(u)}, \forall u \in U, \forall t \in T, a = 1 & [11.1] \\ I_{r(a-1)u(t-1)}^U + \sum_{i \in I_{(Ku)}} Y_{raiut} + \sum_{e \in E} \sum_{k \in K_{(u)}} w_{raekut} - M_{raut} \quad \forall r \in R_{(u)}, \forall u \in U, \forall t \in T, \forall a \ge 2 & [11.2] \\ I_{rau0}^U + \sum_{i \in I_{(Ku)}} Y_{raiut} + \sum_{e \in E} \sum_{k \in K_{(u)}} w_{raekut} - M_{raut} \quad \forall r \in R_{(u)}, \forall u \in U, t = 1, \forall a \ge 2 & [11.3] \end{cases}$$

[12] $$\sum_{r \in R_{(u)}} \sum_{a \in A} I^{U}_{raut} \quad \leq \quad b^{S}_{ut} \quad \forall u \in U, \forall t \in T$$

[13] $$\sum_{a \in A} I^{U}_{raut} \quad \geq \quad b^{\min}_{rut} \quad \forall r \in R_{(u)}, \forall u \in U, \forall t \in T$$

[14] $$\sum_{a=a_c^-}^{a_c^+} D_{raunt} \quad \leq \quad v^{\max}_{rucnt} \quad \forall r \in R_{(u)}, \forall u \in U, \forall c \in C, \forall n \in N, \forall t \in T$$

[15] $$\sum_{a=1}^{a_{u'}^{\max}} \sum_{i \in I \cap I_{(Ku')}} S_{raiu't} \quad = \quad d^{\log}_{ra_{u'}^{\max}u't} \quad \forall r \in R_{(u')}, a_{u'}^{\max} \in A, \forall u' \in U', \forall t \in T$$

[16] $$\sum_{a=1}^{a_u^{\max}} \left( \alpha_{rau} M_{raut} - \sum_{n \in N} D_{raunt} \right) \quad = \quad d^{endproduct}_{ra_u^{\max}ut} \quad \forall r \in R_{(u)}, a_u^{\max} \in A, \forall u \in U, \forall t \in T$$
$$where \quad \alpha_{rau} \in [0;1]$$

[17] $$\sum_{a=1}^{a_u^{\max}} \left( \sum_{r \in R_{(s)}} \gamma_{rau} M_{raut} \right) \quad \geq \quad d^{chips}_{sa_u^{\max}ut} \quad \forall s \in S, a_u^{\max} \in A, \forall u \in U, \forall t \in T$$
$$where \quad \gamma_{rau} \in [0;1]$$

[18] $$X_{it}, I^{F}_{rait} \quad \geq \quad 0 \quad \forall r \in R, \forall a \in A, \forall i \in I$$

[19] $$Y_{raiut}, I^{U}_{raut}, M_{raut}, D_{raunt} \quad \geq \quad 0 \quad \forall r \in R_{(u)}, \forall a \in A, \forall i \in I_{(Ku)}, \forall u \in U, \forall n \in N, \forall t \in T$$

[20] $$S_{raiu't} \quad \geq \quad 0 \quad \forall r \in R, \forall a \in A, \forall i \in I \cap I_{(Ku')}, \forall u' \in U', \forall t \in T$$

[21] $$H_{it} \in \{0,1\} \quad \forall i \in I, \forall t \in T$$

**Objective function**

The objective function is a linear profit maximization equation. Revenues are derived from the sale of lumber and wood chips on the open market. Lumber and chips are always sold in the period they are produced. Note that revenues associated with the sale of logs and end products covered under agreements as well as costs incurred to buy logs from other suppliers have been omitted from the objective function since they are irrelevant to the decision problem at hand. These are covered under binding contracts and are thus parameters to the problem. The first term in equation [1] represents the total revenues from the sale of excess production of end products on the open market, net of the mill's processing costs. The second term corresponds to revenue from the sale of wood chips. It is assumed that all chip production is sold to a single client; therefore the same rate is applied to every unit of chips produced.

Even if revenues from the sale of logs are irrelevant to decision making, the costs incurred to satisfy these demands are important to take into account, as contracts specify the unit price agreed upon to deliver the volumes of desired logs. By satisfying demands from low cost operations, a firm may increase its profit. The third and fourth terms accounts for harvesting costs and stumpage fees. Harvesting costs include all activities occurring from the stump to roadside. The fifth and sixth terms correspond to transportation costs from the forest to the mills (i.e. owned and others' mills respectively). Storage costs are accounted for in the last two terms of equation [1].

This model sets production targets per period. The length of a period is such that more than one block can be visited within the same period. The scheduling of blocks, or the sequence in which blocks are harvested within a period is dealt with at the operational level as it requires considering each contractor's capacity and each scheduling alternative.

**Constraints**

Equation [2] ensures that harvested volumes on a block do not exceed availability. Equations [3] through [5] are used in order to avoid excessive equipment transportation needs. Equation [3] assigns a value to the binary variables, while [4] and [5] limit respectively the number of periods over which harvesting can occur on block *i* and the number of blocks on which harvesting can occur during period *t*. Each mill is limited in the volume of a given resource type that it can receive can be delivered to it from a specific procurement area, as outlined in its TL. The first term of equation [6] refers to volumes delivered from the firm’s own operations while the second term corresponds to volumes bought from other suppliers working in the procurement areas covered by the firm’s TL. The latter are known because they are specified in pre-established contracts between two firms. They are important to take into account since they will have an impact on volumes that can be delivered to its own mills from the firm’s operations.

Next, production constraints limit the total production capacity. Equations [7], [8] and [9] represent respectively the total harvesting, transportation and individual mill’s processing capacity. Aggregated harvesting and transportation capacities are considered rather than individual contractor’s capacity since no contractor scheduling is attempted.

Equations [10.1] through [11.3] represent classical flow conservation constraints. Our formulation of the problem uses a discrete notion of time where the age *a* of harvested wood and periods *t* are both expressed in the same unit (i.e. weeks). As soon as standing timber is harvested, it is assigned an age of 1. The age of the harvested timber evolves with the passing of periods. In equations [10.1] and [11.1], there is no inventory held from period *t-1* because the constraints are concerned with the stocking of harvested wood of age $a = 1$, which means that the wood is stored during the same period it is harvested. Equations [10.3] and [11.3] allow for transition between subsequent planning horizons. Our formulation of the problem takes into account storage into two location types: roadside and mill yard. Storage at roadside is virtually unlimited and requires no capacity constraint although it could easily be added if required. Storage capacity at the mill is limited by equation [12]. Finally, to allow for the planning of resources safety stocks, equation [13] sets a minimum level of inventory to maintain at a given mill at the end of any given period.

A firm must satisfy demands for various commodities: logs, end products and chips. Demands originate from contracts and are considered to be binding. No penalties are incurred for delayed deliveries or missed freshness. However it may be added as presented in Wee and Wang (1999), which model a production-inventory system for deteriorating items with time-varying demands and completely backlogged shortages. Satisfaction of demand for logs, end products and chips are expressed respectively by equations [15], [16] and [17]. Also, because these commodities are used by mills for which the quality level of the input has a direct impact on the performance of their processes and the quality of their end-products, mills have specific requests on the freshness of their input. Our model does not distinguish between end clients since delivery costs are voluntarily omitted. Also, storage and related deterioration of end-products is not considered, although this would be possible as presented in Maness (2002). Market conditions for end-products are modeled using market anticipation functions. These functions use valuation levels which are bounded by a maximum volume of end product that can be sold as represented in equation [14].

# Test case description

For the computational experiment, a hypothetical but realistic test case has been developed based on a firm’s data from the Mauricie region in Quebec, Canada. It represents a typical situation of several forest companies. The company operates two softwood lumber mills within the same region. Mills are provided with raw material from the company’s forest operations and from outside suppliers (other companies’ operations). The list of blocks included in the case study corresponds to the blocks planned to be harvested in the first year of the five year development plan. Table 1 gives an example of data used in the case study.

**INSERT TABLE 1**

The block number, its related procurement area, and the quantities of each assortment are given. In the test case, 50 harvesting blocks are eligible for harvesting during the year. Each block holds a specific volume and composition of resources. 14 different resources are considered, each belonging to one of 4 tree species present. Planning is done for the whole year which is divided into 28 periods of variable duration. Also, 11 different ages are considered to represent the fiber freshness, which have been grouped within 3 age classes. Furthermore, 4 valuation levels are considered for each age class in a market anticipation function.

The test case problem is defined by nearly 300 000 continuous and 1400 binary variables and more than 100 000 constraints. Through Monte Carlo sampling and using probability distribution (see table 3), 11 scenarios have been created, one of which, referred to as the "average scenario", uses the average values of the distribution.

Only standard deviations expressed in percentage of the average value are presented in Table 2 to preserve confidentiality on operations and costs. Standard deviations for stumpage fees and valuation levels have been assigned increasing values over time to reflect the fact that uncertainty increases as the occurrence of an event becomes more distant in time.

**INSERT TABLE 2**

# Results and discussion

## Deterministic wood procurement planning model

The deterministic problems were solved with CPLEX 9.1 on a 2.00 GHz Pentium 4 personal computer with 1.00GB of RAM memory. It took less than five minutes to solve each of them within a relative gap of 5%. Computing time makes it conceivable to use the proposed model on a regular basis to generate many candidate plans and with a rolling horizon in order to periodically adjust the procurement plan when new developments must be considered.

Age tracking along with market anticipation is effective in managing the wood flow from the forest to the mill in order to maximize value. As is shown by Figure 4, the age of volumes planned to be processed through the mills is coherent with valuation function provided for the test case. More than 67% of the total volume is a week old or less, and close to 85% is equal or less than 2 weeks of age. The model has also been tested with bell-shaped valuation functions characterising processing costs at an OSB mill. Similar proportions were obtained with the bulk of production at and around the preferred freshness.

**INSERT FIGURE 4**

### Simulation

In order to assess the impact of uncertainty, each candidate plan has been evaluated under alternate scenarios using the rule-based simulation approach described previously. Through the simulations, metrics pertaining to average and standard deviation of profit, volumes to be acquired from private woodlot owners, and the feasibility of a plan have been gathered.

Average profit and standard deviation have been plotted in Figure 5 for comparison. Analysis using both metrics helps draw a more comprehensive picture of the range of profits and, thus, the associated financial risk that can be expected from the implementation of a plan.

**INSERT FIGURE 5**

Two observations can be drawn from Figure 5. First, the average plan is not the most profitable plan; 4 out of 10 plans show higher profits. In average, plan 9 should generate $467 000 or 8.8% more in profit than the average plan. Second, the ranges in profits that can be expected from the implementation of a plan vary greatly from one plan to another when evaluated from the same scenario sample. Plan 5 shows less variability around the mean than any other plan while the variability of plans 7, 9 and 10 is over twice that of plan 5. The average plan shows a 71.6% higher variability than plan 5.

For every plan, the average volume missing in order to satisfy end products and wood chips engagements is presented in Figure 6. It is important to notice that in general, the implementation of any plan requires the purchase of volumes from private woodlot owners even if the original problems were constrained to satisfy all demands. This is a direct result of the uncertainty associated with capacities and process yields. In most cases, an appropriate level of safety log yard inventory should absorb these fluctuations. Again, the average plan is not the best plan based solely on this metric, 4 plans out of the 10 require buying lesser volumes.

**INSERT FIGURE 6**

Plans feasibility is shown in Table 3. This metric identifies the proportion of scenarios under which it remains feasible. Feasibility varies greatly from one plan to another. Plan 7 shows little overall feasibility. Still, several plans remained fully feasible in all scenarios. On the contrary, the average scenario performed poorly showing feasibility in only 50% of the scenarios.

**INSERT TABLE 3**

## Decision Making

At the end of this planning exercise, a plan has to be selected for implementation. Figure 7 presents the set of candidate plans being considered. In a multiobjective optimization problem, a multitude of solutions may be considered feasible. However, only a subset of these solutions is of interest. The subset of non dominated solutions forms the tradeoff surface (Pareto front) represented by a bold line in figure 7. In our test case, only candidate plans 3, 5, 8 and 9 are non dominated and deserve further analysis. The other metrics described previously can be used, for example, in order to rank non dominated plans according to the decision maker’s preferences.

However, considering recourse actions could attenuate the importance of the financial risk criterion used into identifying the Pareto front by providing opportunities not considered in our approach which could generate higher profitability. Multi criteria decision making being outside the scope of this paper, we refer the reader to Collette and Siarry (2004), for further details on the subject. Further testing using a larger number of scenarios would be required to determine if the average plan would always be among the dominated solutions.

**INSERT FIGURE 7**

Once a plan has been picked for implementation, other information can be advantageously used. For example, harvesting and transportation capacity requirements per period can be extracted and utilized to adjust available capacity levels by hiring or dismissing contractors when possible. Also, unused mills processing capacity is identified and can be used to determine the volume of logs to be purchased from private woodlot owners and to schedule delivery time.

From the test case, none of the plans provide the entire volume of fiber to which the mills are entitled to under their TL. This cannot be attributed to harvest or transportation capacity since used capacity is lower than or equal to available capacity in every period. Also, according to market valuation for end products manufactured by the mills, it should be advantageous for the mills to process all the fiber they are allowed to. The problem arises from the fact that most stands to be harvested are mixed, which means that several tree species are present on the same block. A mill may have rights to only some of them, while harvesting cost and stumpage fee for all the volumes harvested are incurred regardless of whether it is required or not. Unless the undesired or excess harvested volumes are to be delivered to other companies' mills, it is uneconomical to harvest. These stands become economically viable only if the undesirable volumes can be passed along with their associated costs to another firm. This highlights the joint dependency of companies sharing a same procurement area. This also serves to demonstrate the importance of collaboration between these firms in order to optimise their operations.

# Conclusions and future work

Wood procurement planning is by nature a very complex process. This paper introduces a detailed model that supports the centralized wood procurement planning of a company which may include many mills and allows for wood exchanges between companies. We presented an extension of the market mechanism of Maness (1989) to take fiber freshness into consideration and included notion of quality linked to the age of the fiber into demands. We also presented a planning process permitting the generation and evaluation of alternative plans in an uncertain environment.

Results show that it is possible to manage the fiber flow from the stump to end market considering its freshness in order to extract higher value from the logs processed in the mills. Close to 85% of the total volume planned to be processed at the mill sites is of an age of two weeks or less, meaning that even in the warmer months of the year, fiber deterioration is limited. Furthermore, the tested plans show little stability to uncertainty, as significant differences arise from one plan to another. However, computing time of less than five minutes makes it conceivable to use the proposed model with a rolling horizon in order to periodically adjust the procurement plan when new developments must be considered, and to even directly consider recourse in the simulation-based analysis of robustness.

Nowadays, planning is still largely done using intuition with few or no mathematical programming support. Yet, examples of benefits can be found in the literature suggesting an increase (decrease) in profits (costs) averaging 5% when decisions are supported by deterministic mathematical programming (Burger 1991, Williamson and Nieuwenhuis 1993, Hecker *et al.*

2000, Bergdahl *et al.* 2003). The described planning process permitted to identify a plan generating an average of 8.8% more profits than the average plan found using the proposed deterministic model alone. This result makes us anticipate significant benefits from using the proposed model and planning process, as compared to the actual manual planning process. However, potential benefits are highly dependent on factors such as the spatial distribution of harvest blocks and mills, the stand composition, the number of beneficiaries on the same procurement areas and the level of uncertainty. The higher the uncertainty, the higher is the potential gain.

Results also demonstrate that using a deterministic model in a non deterministic environment can yield false expectations and stresses the importance of analyzing and validating the so-called optimal plan. From our test case, the optimal deterministic plan is not the optimal plan when uncertainty is considered. Also, the optimal deterministic plan does not satisfy all demands when simulated in different scenarios, even though it was constrained to do so in the deterministic model. Moreover, it does not give any indication on the financial risk, nor the risk associated to the feasibility of the plan incurred by its implementation. A plan obtained from optimizing average parameter values should not be considered as the optimal plan to be implemented as is, but should rather be looked at as a first cut solution or merely a plan from which to build from.

Also, our deterministic model generated candidate plans which do not dictate harvesting all the allowable volume to which mills were entitled to under their TL. This result reflects the situation experienced by most companies sharing procurement areas in eastern Canada. Therefore, further developments are being undertaken to look at the interdependency of companies sharing the same procurement areas and ways to facilitate their needed interactions will be explored.

Also, considering recourse actions could attenuate the importance of the financial risk criterion used for identifying the Pareto front by providing opportunities not considered in our approach. These new opportunities could generate higher profitability. Therefore, a recourse mechanism will be included into the planning process in order to make new planning decisions as events unfold such as in Myers and Richard (2005).

Finally, the deterministic model presented in this article, when used in combination with the harvest block sequencing and equipment transportation model introduced in Beaudoin *et al*. (2005), allows for cost/value analysis. These analyses will examine tradeoffs between an increase in equipment transportation cost and reductions of costs incurred by holding inventories, opportunity cost, opportunity lost and lost of value caused by fiber deterioration.

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# References

Beaudoin, D., Frayret, J.M., LeBel, L. 2005. Harvest Block Sequencing and Equipment Transportation Anticipation Model. Working Paper, CENTOR. 41 p.

Bergdahl, A., Örtendahl, A. and Fjeld, D. 2003. The economic potential for optimal destination of roundwood in North Sweden – Effects of planning horizon and delivery precision. Int. J. of Forest Engineering, Vol.**14**(1):1-15.

Bicho, P. 2002. Chip storage issues. *In* Proceedings of the Conference: Wood Storage: Issues and Solutions, March 26 2002, Pointe- Claire, Qc. *Edited jointly by* For. Eng. Inst. Of Canada, Pulp and Paper Res. Inst. Of Canada and Forintek Canada Corp., Pointe-Claire, Qc. CDRom.

Burger, D.H. 1991. Master Thesis. Analysis of wood procurement and distribution problems using linear programming. University of New-Brunswick, Canada.

Burger, D.H., and Jamnick, M.S. 1995. Harvest and distribution decisions. For. Chron. **71**(1): 89-96.

Carlsson, D., Rönnqvist, M., and Westerlund, A. 1998. Extraction of logs in forestry using operations research techniques. Linköpings Universitet. LiTH-MAT-R-1998-17.

Collette, Y. and Siarry, P. 2004. Multiobjective Optimization – Principles and Case Studies, 2nd ed. Springer-Verlag Berlin Heidelberg, Germany. 270p.

Davis, T. 1996. Effective Supply Chain Management. Sloan Management Review. **34**(4): 35-46.

Frayret, J.-M., D'Amours, S., and Montreuil, B. 2004. Co-ordination and control in distributed and agent-based manufacturing systems. Production Planning Control. **15**(1): 1-13.

Gingras, J.-F., and Sotomayor, J. 1992. Les variations de teneur en humidité du bois dans les opérations forestières: une étude de cas. Inst. Ca. De rech. En génie for. Fiche technique FT-192.

Goetschalckx, M., Ahmed, S., Shapiro, A., and Santoso, T. 2001. Designing flexible and robust supply chains. *In* Proceedings of the 3rd International Conference on Industrial Engineering and Production Management (IEPM), 20-23 August 2001, Quebec City, Quebec. pp. 539-552.

Hecker, M., Becker, G. and Ressmann, J. 2000. Estimating benefit potentials in german logistics for wood procurement and timber logging. Logistics in the Forest Sector, Kim Sjöström (editor), Helsinki.

Karlsson, J.; Rönnqvist, M., and Bergström, J. 2004. An optimization model for annual harvest planning. Can. J. For. Res. **34**: 1747-1754.

Karlsson, J., Rönnqvist, M., and Bergström, J. 2002. Short-term Harvest Planning Including Scheduling of Harvest crews. Linköpings Universitet. Working Paper.

Kreber B., Kimberley, M., Eden, D., Chittenden, C., Van Der Waals, J., Wakeling, R., and Dorset, I. 2001. Arrest of fungal pre-infections in raw logs and freshly sawn lumber of radiate pine using Sentry®. For. Prod. J. **51**(10): 66-72.

Laganière, B., and Defo, M. 2002. Moisture content affecting efficiency of sawmill and OSB Plants. *In* Proceedings of the Conference: Wood Storage: Issues and Solutions, March 26 2002, Pointe- Claire, Qc. *Edited jointly by* For. Eng. Inst. Of Canada, Pulp and Paper Res. Inst. Of Canada and Forintek Canada Corp., Pointe-Claire, Qc. CDRom.

Maness, T.C. 1989. A technique for the combined optimization of sawing and bucking strategies. Ph.D. Dissertation, Univ. of Washington, Seattle, WA, USA. 198p.

Maness, T.C., and Norton, S.E. 2002. Multiple Period Combined Optimization Approach to Forest Production Planning. Scand. J. For. Res. **17**: 460-471.

Martell, D.L., Gunn, E.A., and Weintraub, A. 1998. Forest management challenges for operational researchers. European Journal of Operation Research **104**: 1-17.

Myers, J.A., and Richards, E.W. 2005. Analyzing Robustness of Forest Operational Plans using Optimization and Simulation. 47th Annual Conference of the Canadian Operational Research Society, May 16-18, Halifax, Canada.

Novak, D.C., and Ragsdale, C.T. 2003. A decision support methodology for stochastic multi-criteria linear programming using spreadsheets. Decision Support Systems **36**(1): 99-116.

Shapiro, J.F. 2001. Fundamentals of Optimization Models: Linear Programming. *In* Modeling the Supply Chain. Duxbury – Thomson Learning, California, USA. pp. 63-124.

Van Landeghem, H., and Vanmaele, H. 2002. Robust planning: a new paradigm for demand chain planning. Journal of Operations Management **20**: 769-783.

Wee, H.M., and Wang, W.T. 1999. A variable production scheduling policy for deteriorating items with time-varying demand. Computers and Operations Research. **26**: 237-254.

Weintraub, A., and Bare, B.B. 1996. New issues in forest land management from an operations research perspective. Interfaces **26**: 9-25.

Wightman, R., and Jordan, G. 1990. Harvest distribution planning in New Brunswick. CPPA Woodlands Paper, August: 19-22.

Williamson, G. and Nieuwenhuis, M. 1993. Integrated Timber Allocation and Transportation Planning in Ireland. Int. J. of Forest Engineering, Vol.**5**(1): 7-15.

Wood, J. 2002. Pulp production affected by storage period. *In* Proceedings of the Conference: Wood Storage: Issues and Solutions, March 26 2002, Pointe- Claire, Qc. *Edited jointly by* For. Eng. Inst. Of Canada, Pulp and Paper Res. Inst. Of Canada and Forintek Canada Corp., Pointe-Claire, Qc. CDRom.

Yang, D.-Q., Gagné, P., Uzunovic, A., Gignac, M., and Bernier L. 1999. Development of fungal stain in logs of three canadian softwoods. For. Prod. J. **49**(2): 39-42.

Yang, D.-Q., and Beauregard, R. 2001. Check development on Jack pine logs in eastern Canada. For. Prod. J. **51**(10): 63-65.

# Tables

**Table 1.** Example of information used for 5 blocks.

| Block | Proc. Area | Spruce | | Balsam | | Pine | | Birch | | | | Maple | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | A | B | A | B | A | B | C | D | A | B | C | D |
| 6 | 41-01 | 736.5 | 1269.4 | 1490.0 | 2637.9 | – | – | – | 104.0 | 323.6 | 102.2 | – | 97.2 | – | – |
| 8 | 41-01 | 807.3 | 189.4 | 716.8 | 774.8 | 1594.6 | 990.4 | – | – | – | – | – | – | – | – |
| 16 | 42-02 | – | – | 716.4 | 764.9 | 499.6 | – | – | – | – | – | – | 51.1 | 96.5 | 51.4 |
| 19 | 42-02 | 1075.9 | 1913.6 | – | – | – | – | – | 26.1 | 80.8 | – | 25.2 | 75.3 | 101.3 | – |
| 22 | 43-04 | 975.1 | 3086.7 | 2047.8 | 4053.8 | – | – | 99.9 | 203.9 | 101.5 | 103.1 | – | 51.7 | 51.7 | – |

**Table 2.** Example of probability distribution used in Monte Carlo sampling.

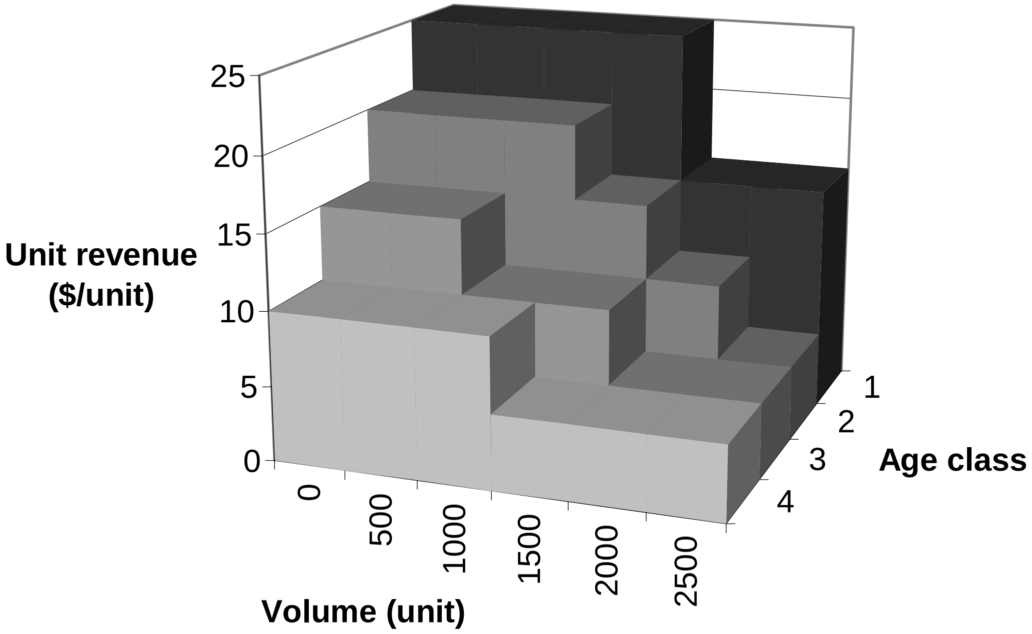
| Factors | Standard deviation |
|---|---|
| Supply | |
| Standing inventories | 3.5% |
| Stumpage fees | 1-5% |
| Production | |
| Productivity | |
| Harvesting costs | 2% |
| Transporting costs | 3.5% |
| Capacity | |
| Harvesting | 4% |
| Transporting | 4% |
| Storing | 1-4% |
| Milling | 3% |
| Yield coefficients | |
| End products | 2% |
| Chips | 2% |
| Clients | |
| Valuation Levels | 1-5% |

**Table 3.** Plan’s feasibility.

| | Plan | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Feasibility (%) | 90 | 70 | 100 | 100 | 100 | 100 | 10 | 100 | 60 | 90 | 50 |

# Figures

**Fig. 1.** Example of a mill valuation function for a given resource over a determined season.



658 **Fig. 2.** Planning process.

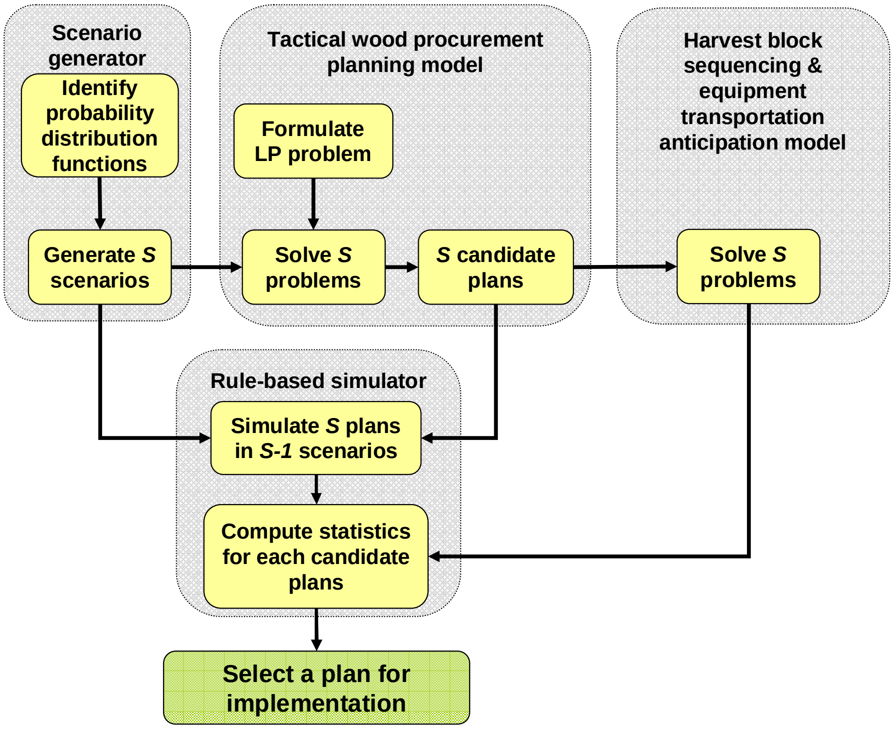


**Fig. 3.** Illustration of the wood procurement planning problem.

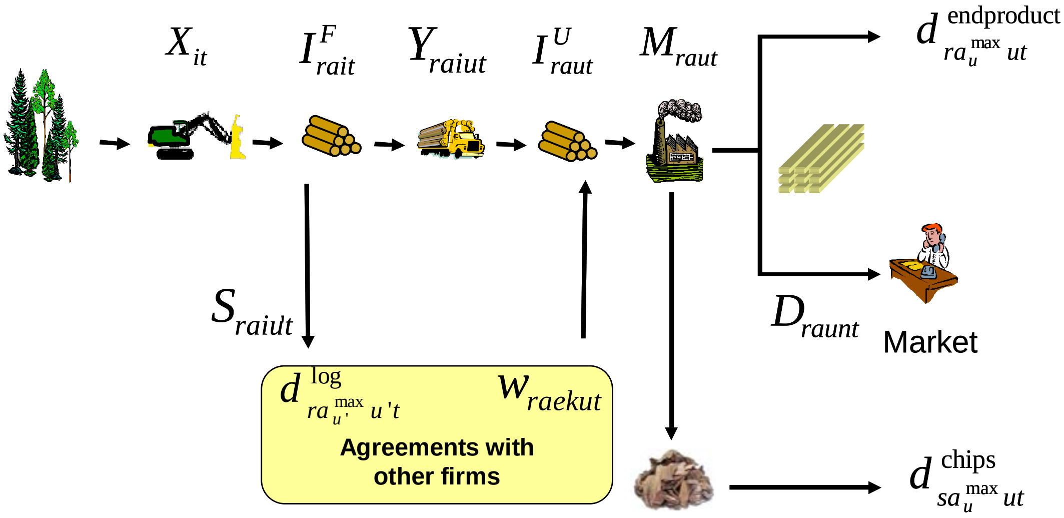


**Fig. 4.** Freshness of logs processed through the mills.

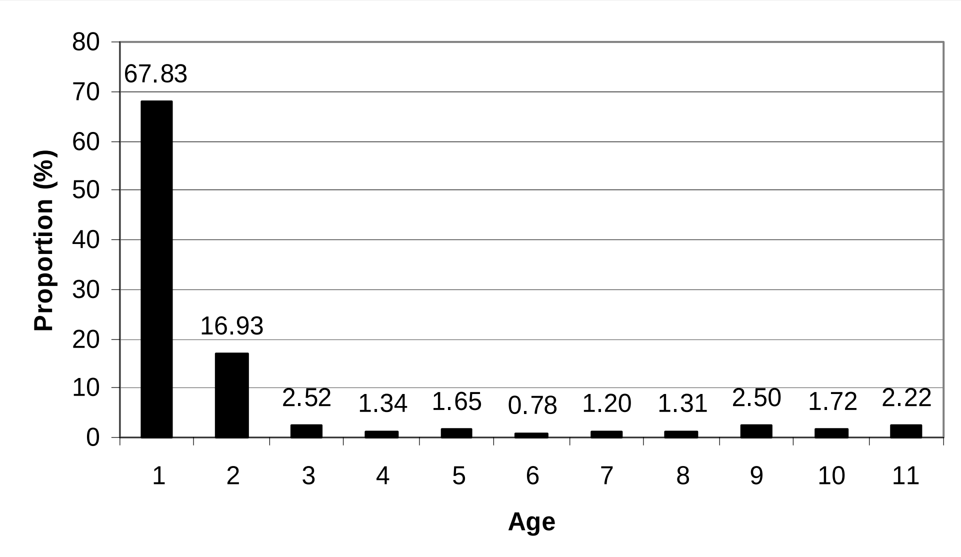


**Fig. 5.** Average plan's profitability and associated standard deviation.

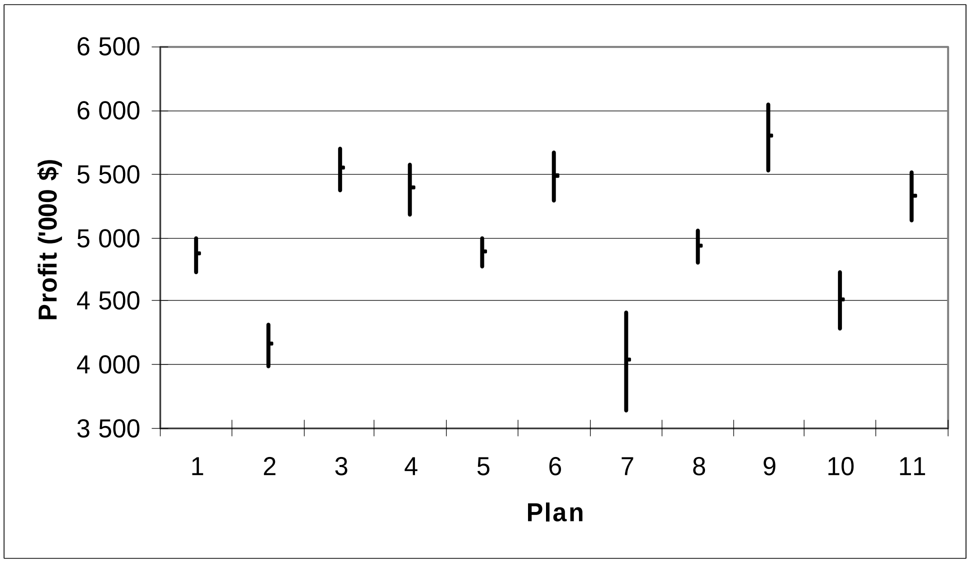


**Fig. 6.** Volumes to be purchased from private woodlot owners.

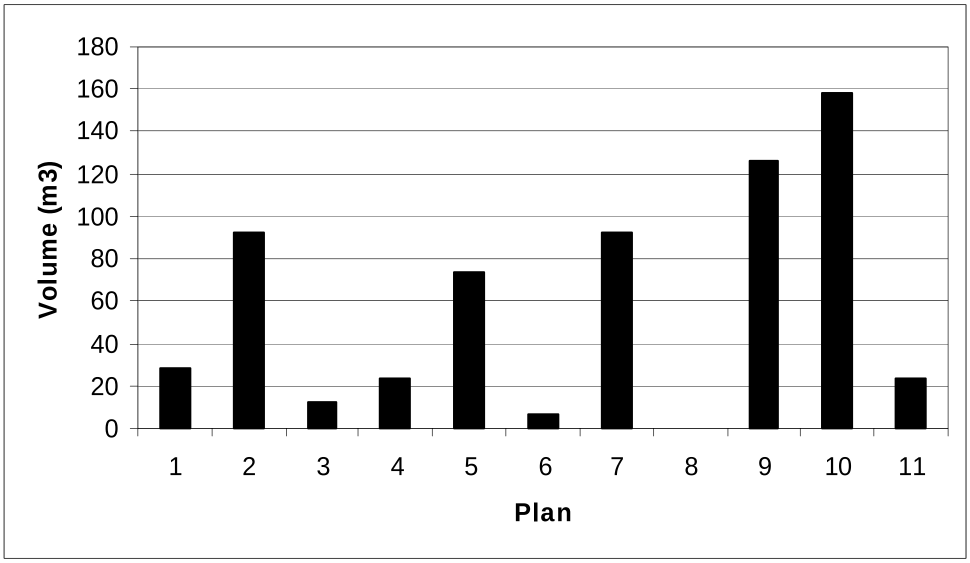


**Fig. 7.** Tradeoff surface.