International Conference on Industrial Engineering and Systems Management
IESM 2005, May 16 – 19, Marrakech (Morocco)

Supply optimization for a pulp and paper mill network

H. Bouchriha(2), M.A. Mammou(1), S. D'Amours(1), A. Hadj Alouane(2)
(1) Research Consortium in e-business in the forest products industry
Université Laval – CANADA
(2) École Nationale d'Ingenieurs de Tunis

Abstract.

A real case of procurement planning of wood fiber between a paper mill and fiber suppliers, e.g. sawmills, is modelled and validated. Several sourcing options are available to the paper mill (in-house sawmills, external sawmills, trading sawmills, and partners). The model optimizes the choice of suppliers, determines the supply option (contract or spot market) and decides the quantities to order for each period as well as the contractual annual volume guarantee.

1. Introduction

Forest operations, sawmilling and paper making are three interdependent activities. Synchronizing the flows between sawmills and paper mills can reduce the procurement costs. It is within this framework that this project is conducted. More precisely, its objective is the procurement planning of wood fiber between paper mills belonging to a given company, in-house sawmills, external sawmills, trading and affiliated sawmills.

Paper mills can either sign long-term contracts defining year based volume guarantee, or use the spot market to satisfy their demand. The advantages of contracts are to stabilize procurement and to get better prices and better payment terms. Hence, the signature of contracts on a periodic basis makes it possible to cover risks (such as fiber shortage in the market, forest fires, fiber price increases, etc.), provides a guarantee on the provisioning volumes and price stability. In the case of the spot market, sawmills try to liquidate their production surplus. This can help paper mills obtain their additional requirements of fiber.

The literature on contracts concerns essentially two fields:

- **The economic literature**: it considers the relationship between supplier and producer as two independent agents acting in their own best interests. This point of view ignores global optimization of the problem. The contributions mainly study the nature of relationships and the incentive actions to establish in order to better confront risk (For more details on works in this field, readers are referred to [10] [17])
- **The supply chain literature**: it considers the nature of contracts along the supply chain. The general goal is to develop rules and mathematical models for material accountability and/or pricing that will guide autonomous entities towards globally desired outcomes [18]. Recent reviews in this field can be found in [3] and [19]. Main studies can be classified as follows [11]:
  - Pricing [7] [15] [21] [22]
  - Minimum purchase commitment [4] [8]
  - Contract period [5]
  - Lead time [9] [16]
  - Quantity flexibility [2] [12] [14] [18] [20]

- Quality [1] [13]

The literature review on contract reveals that there is no study on optimizing fiber supply contracts in the pulp and paper supply chains. The aim of this article is to propose an optimization tool for fiber procurement to determine the sawmill to choose (in-house, external, trading, affiliated), the best supply option for each sawmill (spot or contract) in order to minimize total supply and inventory costs, guarantee maximum quality for fiber to be bought and decide which quantity to buy for each period from each sawmill.

In the second section, we describe a case study that illustrates the case of an integrated company in the pulp and paper field, a partner of the FOR@C Research Consortium. In the third section, we present the mathematical model developed to solve the problem. In the fourth section, some computational results and scenario analysis are presented.

2. Case study

The problem addressed in this article is building upon a real case study of fiber supply optimization for an integrated company in the pulp and paper industry. The company has four procurement options for its paper mills:

– In-house sawmills: These sawmills belong to the company as well as the fiber they produce. Hence, when paper mills need wood fiber, these sawmills can produce fiber exclusively for them. Fiber is then bought based on contracts that are signed and negotiated once a year. These contracts fix the quantity that sawmills have to provide for one year and the corresponding price.

– Trading: This option is commonly used in the pulp and paper industry in Canada. As paper mills are located far from sawmills, the latter exchange their fiber with other sawmills that are located closer. The trading option is subject to contract agreements which are signed and revised once a year.

– Affiliated sawmills: The company has a partnership with those sawmills and use contracts to buy their fiber. Contracts are signed once a year and guarantee the quantities volume to be provided by sawmills and the corresponding prices.

– External Sawmills (Third party): The company has the possibility to buy fiber from external sawmills either under contracts or spot market.

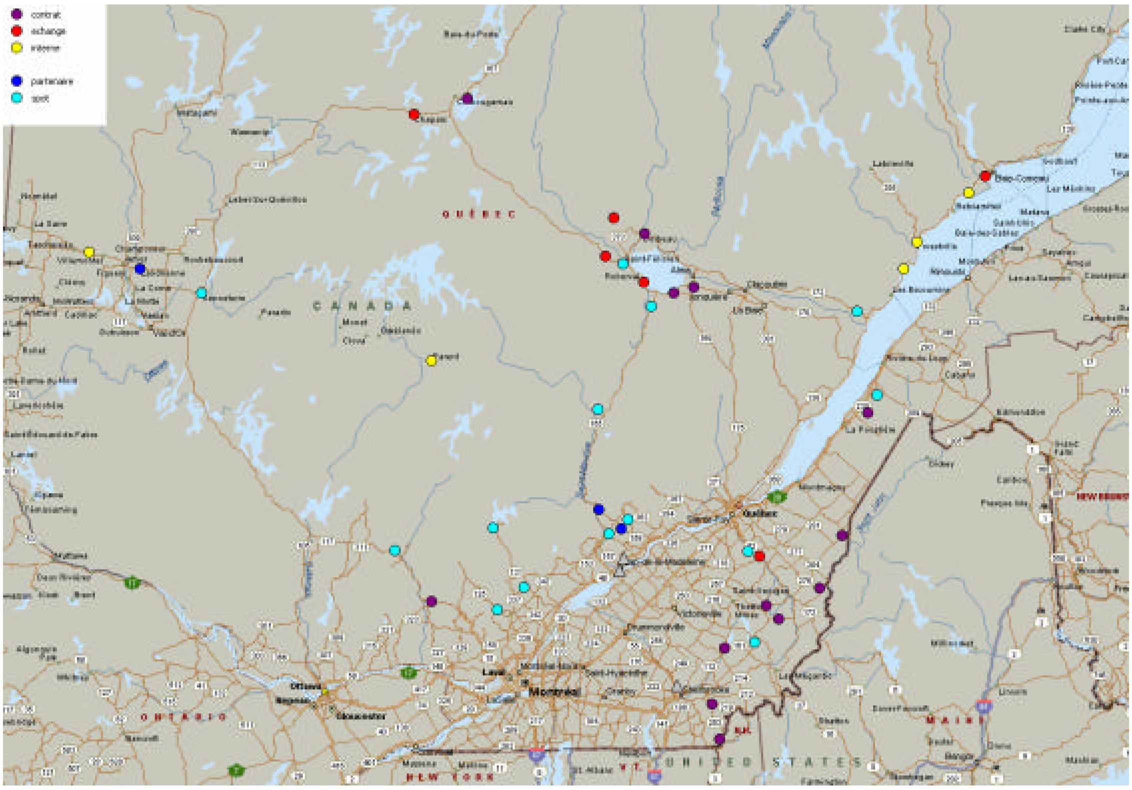

Figure 1 : The network

Specificities related to the studied company are cited below:

- Demand (fiber consumption) is dynamic.
- Purchasing and transportation costs are quantity independent. Hence economies of scale are not considered.
- Maximum delays for the stored items don't cause quality degradation of fiber. Furthermore, we suppose that cutting, sawing and purchasing delays are short and do not affect fiber quality.
- Species received are either pure species or mixture. For sawmills that provide a mixture, the proportion of each species is known and each paper mill fixes requirements for each mixture received.
- All species are mixed in stocks, however fiber consumption is known for all species.
- Only one transportation option is associated with each supplier. For the case studied, there is no constraint on transportation because supply managers can always find transporters to ship their fiber.

3. Model formulation

3.1 Indices and sets

T = set of periods.

P = set of paper-mills

SC = set of external sawmills (third party) with which only contract option is possible.

SS = set of external sawmills (third party) with which only spot option is possible.

SI = set of in-house sawmills with which only contract option is possible.

SA = set of affiliated sawmills (partner) with which only contract option is possible.

SK = set of trading sawmills with which only contract option is possible.

EP= set of pure species.

EM = set of mixed species.

t = a planning period, t $\in$ T.

p = a paper-mill, p $\in$ P.

s = a sawmill, s $\in$ S=SC $\cup$ SS $\cup$ SI $\cup$ SA $\cup$ SK.

e = a product (wood fiber) species, e $\in$ E=EM $\cup$ EP.

3.2 Data

$X_{p,t}$ = Fiber consumption per period t and paper mill p (TMA)

$A_{p,s,e}$ = Fixed supply cost of pure species e $\in$ EP, for contract market between external provider (s $\in$ SC $\cup$ SS) and paper mill p ($)

$A_{p,s,mix}$ = Fixed supply cost of the mixture for contract market between external provider (s $\in$ SC $\cup$ SS) and paper mill p ($)

$P_{p,s,e}$ = Variable supply cost for fiber type e (e $\in$ E=EM $\cup$ EP) provided by sawmill s (s $\in$ S) to paper mill p ($/TMA[1]).

$q_{p,s,e}$: Correction factor related to the penalty paid by paper mill p according the quality of deliveries of fiber type e (e $\in$ E=EM $\cup$ EP), provided by sawmill s (s $\in$ S).

$h_{p,e,t}$ = Unit inventory cost for fiber type e (e $\in$ E=EM $\cup$ EP) at the paper mill p and period t ($/stock unit. period).

$\bar{Q}_{p,s,e,t}$ = Maximum quantity of fiber species e (e $\in$ EP) that can be provided by sawmill s (s $\in$ S) to paper mill p in period t (TMA).

$\bar{Q}_{p,s,mix,t}$ = Maximum quantity of mixture to be shipped by sawmill s (s $\in$ S) to paper mill p, in period t.

S_p^{max} = Maximum stock level for fiber at paper mill p.

S_p^{min} = Safety stock level for fiber at paper mill p (reached Saturday night because there are no deliveries on weekend).

$R_{e,p}$ = proportion of species e of fiber required at paper mill p.

$a_{p,s,e}$ = percentage of fiber e (e $\in$ EM) in the mixture provided by supplier s (s $\in$ S) to paper mill p.

$X_{p,t}$ = Quantity of fiber consumed by paper mill p in period t.

M = A very large number.

---

[1] Weight unit for fiber : Anhydrous Metric Ton.

3.3 Decision variables

$Q_{p,s,e,t}$ = Quantity of species e (e $\in$ E=EM $\cup$ EP) of fiber ordered by paper mill p from supplier s (s $\in$ S) on period t.

$Q_{p,s,mix,t} = \sum_{e\in\{1..EM\}} Q_{p,s,e,t}$ = Quantity of mixture ordered by paper mill p from sawmill s (s $\in$ S) in period t.

$I_{p,e,t}$ = Stock level of fiber e (e $\in$ E=EM $\cup$ EP) at paper mill p at the end of period t.

$p_{p,s,e}$ = Buying guarantee of species e (e $\in$ E=EM $\cup$ EP) for the paper mill p from sawmill s (s $\in$ SC $\cup$ SI $\cup$ SA $\cup$ SK).

$$d_{p,s,e,t} = \begin{cases} 0 & \text{If } Q_{p,s,e,t} = 0 \text{ ; e} \in \text{EP ; s} \in \text{SC} \\ 1 & \text{If } Q_{p,s,e,t} > 0 \text{ ; e} \in \text{EP ; s} \in \text{SC} \end{cases}$$

$$d_{p,s,mix,t} = \begin{cases} 0 & \text{If } Q_{p,s,mix,t} = 0 \text{ ; s} \in \text{SC} \\ 1 & \text{If } Q_{p,s,mix,t} > 0 \text{ ; s} \in \text{SC} \end{cases}$$

$$d_{p,s,e,t} = \begin{cases} 0 & \text{If } Q_{p,s,e,t} = 0 \text{ ; e} \in \text{EP ; s} \in \text{SS} \\ 1 & \text{If } Q_{p,s,e,t} > 0 \text{ ; e} \in \text{EP ; s} \in \text{SS} \end{cases}$$

$$d_{p,s,mix,t} = \begin{cases} 0 & \text{If } Q_{p,s,mix,t} = 0 \text{ s} \in \text{SS} \\ 1 & \text{If } Q_{p,s,mix,t} > 0 \text{ s} \in \text{SS} \end{cases}$$

3.4 Objective function

$$\text{Minimize } \sum_{s\in SC}\sum_{e\in EP}\sum_{p\in P}\sum_{t\in T} A_{p,s,e} d_{p,s,e,t} + \sum_{s\in SC}\sum_{p\in P}\sum_{t\in 1} A_{p,s,mix} d_{p,s,mix,t} + \sum_{s\in SS}\sum_{e\in 1}\sum_{p\in 1}\sum_{t\in 1} A_{s,p,e} d_{p,s,e,t} +$$

$$\sum_{s\in SS}\sum_{p\in P}\sum_{t\in T} A_{s,p,mix} d_{p,s,mix,t} + \sum_{s\in SC}\sum_{e\in E}\sum_{p\in P} P_{p,s,e}(1+q_{p,s,e})p_{p,s,e} + \sum_{s\in SA}\sum_{e\in E}\sum_{p\in P} P_{p,s,e}(1+q_{p,s,e})p_{p,s,e}$$

$$+ \sum_{s\in SK}\sum_{e\in E}\sum_{p\in P} P_{p,s,e}(1+q_{p,s,e})p_{p,s,e} + \sum_{s\in SI}\sum_{e\in E}\sum_{p\in P} P_{p,s,e}(1+q_{p,s,e})p_{p,s,e} +$$

$$\sum_{s\in SS}\sum_{e\in E}\sum_{p\in P} P_{p,s,e}(1+q_{p,s,e})p_{p,s,e} + \sum_{e\in E}\sum_{p\in P}\sum_{t\in T} h_{p,e,t} I_{p,e,t}$$

The objective function minimizes total purchasing, transportation and inventory costs for all paper mills, all species, all sawmills used and for all planning horizons. The first four terms corresponds to fixed supply costs for external sawmills under spot and contract options. The next four summations represent purchasing costs for respectively in-house, affiliated, trading and external sawmills under contract. These costs depend on volume guarantee. The ninth term is the variable purchasing cost for external sawmills under spot option. This cost depends on the quantity actually purchased. The last term corresponds to total inventory cost.

3.5 Constraints

– Constraint on the mixture :

$$Q_{p,s,e,t} = a_{p,s,e} \sum_{e \in EM} Q_{p,s,e,t} \qquad p \in P\,;\ s \in S\,;\ e \in EM \text{ and } t \in T$$

When suppliers provide mixed species, these constraints fix the proportion of each essence in the mixture.

– Constraint on production capacity of sawmills

$$Q_{p,s,e,t} \le \bar{Q}_{p,s,e,t} \qquad p \in P\,;\ s \in S\,;\ e \in EP \text{ and } t \in T$$

$$Q_{p,s,mix,t} \le \bar{Q}_{p,s,mix,t} \qquad p \in P\,;\ s \in S \text{ and } t \in T$$

These constraints impose an upper bound on the quantity purchased from each sawmill according to its output for each species (pure or mixture) and each period.

– Constraint on inventory level

$$S_p^{\min} \le \sum_{e \in E} I_{p,e,t} \le S_p^{\max} \qquad p \in P\,;\ e \in E\,;\text{ and } t \in T$$

This constraint specifies an upper bound on inventory level related to storage capacity as well as a lower bound related to security stock level

– Constraint on flow conservation :

$$I_{p,e,t-1} + \sum_{s \in SI} Q_{p,s,e,t} + \sum_{s \in SA} Q_{p,s,e,t} + \sum_{s \in SK} Q_{p,s,e,t} + \sum_{s \in SC} Q_{p,s,e,t} + \sum_{s \in SS} Q_{p,s,e,t} = I_{p,e,t} + R_{p,e} X_{p,t}$$

T ∈ T; e ∈ E and p ∈ P

Flow conservation constraints are defined at each paper mill. They force matter assessment for each species (pure or mixture) stored at the site. Hence, the stock level at the end of period t-1 increased by the quantity purchased from sawmills must be equal to the sum of stock levels at the end of period t and fiber consumption of the paper mill for the corresponding species and period.

– Contractual constraint :

$$\sum_{t \in 1} Q_{p,s,e,t} \le p_{p,si,e} \quad p \in P \qquad s \in SC \cup SI \cup SA \cup SK \text{ and } e \in E$$

These constraints make sure that all signed contracts are respected to meet buying agreements (volume guarantees) for the entire planning horizon.

- Constraint on lower bound on contract

$$\sum_{e \in E} \sum_{s \in SI} p_{p,s,e} + \sum_{e \in E} \sum_{s \in SA} p_{p,s,e} + \sum_{e \in E} \sum_{s \in SK} p_{p,s,e} + \sum_{e \in E} \sum_{s \in SC} p_{p,s,e} \ge 0.75 \Big(\sum_{e \in E} \sum_{s \in SI} p_{p,s,e} + \sum_{e \in E} \sum_{s \in SA} p_{p,s,e}$$
$$+ \sum_{e \in E} \sum_{s \in SK} p_{p,s,e} + \sum_{e \in E} \sum_{s \in SC} p_{p,s,e} + \sum_{e \in E} \sum_{s \in SS} p_{p,s,e} \Big)$$

p = 1 ∈ P ; t ∈ T

This constraint imposes a lower bound on the quantity to be purchased under the contract option. This allows limiting risk related to spot market.

– Integrity Constraint

$$Q_{p,s,e,t} \le M d_{p,s,e,t} \qquad p \in P\,;\ s \in SC\,;\ e \in EP \text{ and } t \in T$$

$$\sum_{e \in EM} Q_{p,s,e,t} \le Md_{p,s,mix,t} \qquad p \in P \; ; s \in SC \text{ and } t \in T$$

$$Q_{p,s,e,t} \le Md_{p,s,e,t} \qquad p \in P \; ; s \in SS; e \in EP \text{ and } t \in T$$

$$\sum_{e \in EM} Q_{p,s,e,t} \le Md_{p,s,mix,t} \qquad p \in P \; ; s \in SS \text{ and } t \in T$$

4. Computational results

4.1 Application data

The model developed in the previous section was applied on the horizon of one year, with **52** planning periods. We considered **3** paper mills and a network composed of: **9** in-house sawmills, **10** trading, **7** partners, **23** external sawmills with contract options and **18** external sawmills with spot options. 2 pure species (fir, jack pine) and 2 mixed species (fir and spruce) fiber mixtures are used. By using Cplex, the optimal solution that corresponds to the supply planning for each week and the determination of volume guarantee for each signed contract, is obtained in 16.81 s, with a Pentium 4, 200 GHz, 1.25GB.

4.2 Optimal solution

We compare the optimal solution obtained by our model (without taking into account the quality level of sawmills) with the solution they currently use. Hence, we realize that we can achieve a gain of up to 27% on supply cost.

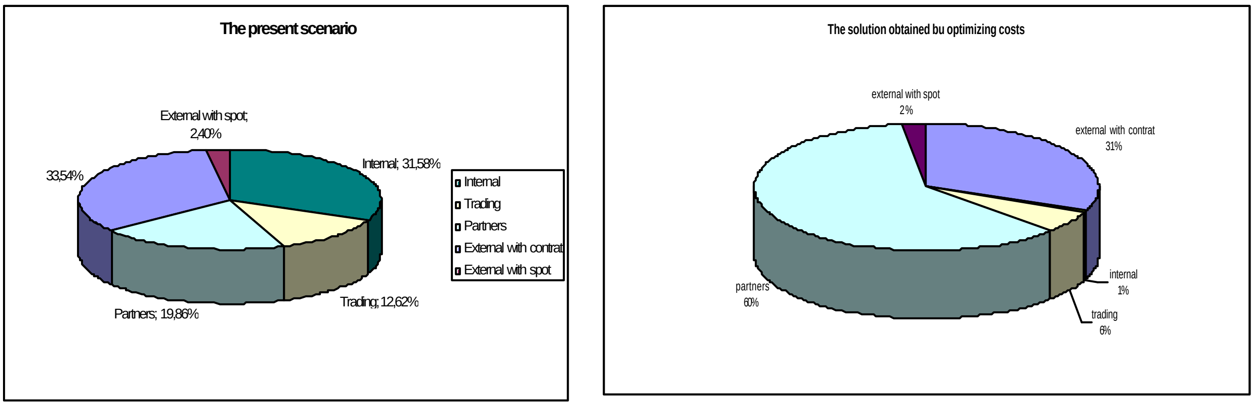

Figure 2 : Comparison between the present scenario and the optimal solution

Figure 2 shows the total quantity to be bought for each option by considering the present scenario and the optimal solution. We can observe a decrease for in-house sawmills as the transportation cost is too high. For trading, volume has also decreased by half. However, supply quantity from partners increases.

4.3 Sensitive analysis

4.3.1 Impact of quality level of suppliers

In the objective function, we consider a corrective factor that depends on supplier delivery quality (we use a historic of sawmill deliveries in order to determine that factor). Hence, if the company decides to buy from a supplier that does not meet its quality requirements it will be more expensive and this situation will be avoided because the model minimizes

costs. Quality is an important criterion in fiber supply because all process parameters depend on it. If the quality is poor, the company has to adjust production parameters and use more bleaching agents to obtain a good quality of paper at the end of the process.
The model was tested by considering quality levels of suppliers and without considering this criterion. The results obtained are presented in Figure 3.

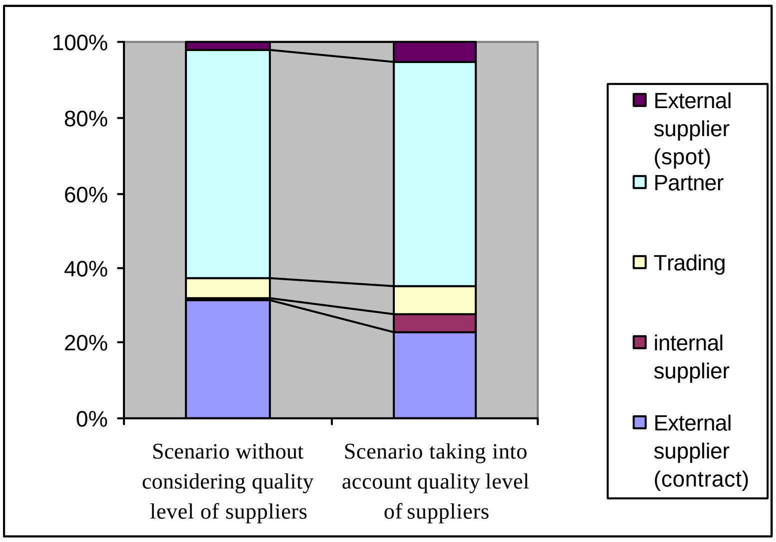

Figure 3 : Impact of quality consideration

We can conclude that taking fiber quality into account will affect the sawmill choice (in-house, external, trading, partner). Hence, the model tends to choose external sawmills (with spot option), in-house sawmills, and trading because these sawmills have better quality than partners and external sawmills with contract option.

4.3.2 Impact of demand variability

We suppose that purchasing a new paper machine implies an increase on demand. We test this scenario with our model and the results are presented in Figure 4. We notice that in this case, the model chooses the spot market as the contract market is used first. Hence, the spot market is essentially used when demand increases to absorb this variability of demand.

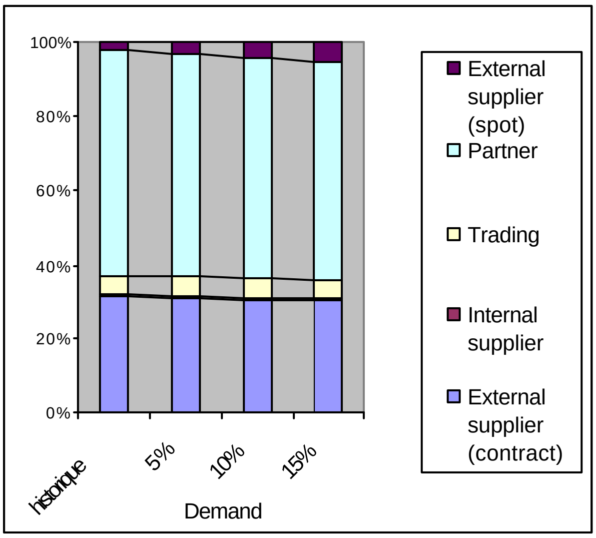

Figure 4 : Impact of demand variability

5. Conclusion

In this paper we have developed and validated an optimization model for fiber procurement for an integrated paper-mill company. The model is used to minimize supply costs taking into account quality. It allows us to:

- choose sawmills and define the best procurement option (contract or spot market),
- establish the quantity to purchase at each planning period and the contractual volume guarantee for each contract option, and
- determine the stock level at the end of each period.

For further research, as the optimal solution does not use in-house sawmills because of transportation costs are too high (far from the paper mill), we can try to optimize trading and integrate other paper mills and their sawmills which will represent potential trading suppliers. This will be done in order to determine the optimum quantity to deal between in-house sawmills and the other potential trading suppliers.

We ca also consider other types of contracts such as contracts that specify periodic guarantied volume and contract duration. This type of contract has been modeled in [6]. Hence we can consider many types of contracts offered by sawmills where volume guarantee and prices depend on the period where the contract is signed as well as its duration.

References

[1] Baiman, S., P.E. Fisher and M.V. Rajan, « Information, Contracting, and Quality Costs» Management Science, 46/6, 776-789, 2000.

[2] Bassok, Y. and R. Anupindi, « Analysis of supply contracts with total minimum commitment» IIE Transactions, 29, 373-381, 1997.

[3] Cachon G.P. Supply chain coordination with contracts, Handbooks in Operations Research and Management Science: Supply Chain Management. edited by Steve Graves and Ton de Kok. North Holland, 229-339, 2003.

[4] Cachon, G.P. and M.A. Lariviere, « Contracting to Assure Supply: How to Share Demand Forecasts in a Supply Chain Management Science, » 47/5, pg 629, 2001.

[5] Cohen, M.A and N. Agrawal, « An analytical comparison of long and short term contracts,» IIE Transactions, 31, 783-796, 1999.

[6] D'Amours S., "La planification des opérations en réseaux manufacturiers symbiotiques", *Thèse de doctorat*, École Polytechnique de Montréal, août 1995.

[7] Donohue, K.L., « Efficient Supply Contracts for Fashion Goods with Forecast Updating and Two Production Modes,» Management Science, 46/11, 1397-1411, 2000.

[8] Grossman, T.A.Jr., T.R. Rohleder and E.A. Silver, « A negotiation aid for fixed-quantity contracts with stochastic demand and production,» International Journal of Production Economics, 66, 67-76, 2000.

[9] Iyer, A.V. and M.E. Bergen, «Quick Response in Manufacturer-Retailer Channels,» Management Science, 43/4, 559-570, 1997.

[10] Katz M. L., Vertical contractual relations. R. Schmalensee, R. D. Willig, eds. Handbook of Industrial Organization, vol. I. Elsevier Science Publishers B.V., New York. Cambridge, MA.1989

[11] Lehoux N., Articles scientifiques portant sur les contrats dans la chaîne logistique, Sujets spéciaux en génie industriel, Université Laval, pg 63, 2001.

[12] Li, C.L and P. Kouvelis, "Flexible and risk-sharing supply contracts under price uncertainty", Management Science, Vol 45, N° 10, Octobre (1999), 1378-1398.

[13] Lim, W.S., « Producer-Supplier Contracts with Incomplete Information» Management Science, 47/5, 709-715, 2001.

[14] Moinzadeh, K. and S. Nahmias, « Adjustment Strategies for a Fixed Delivery Contract» Operations Research, 48/3, pg 408, 2000.

[15] Munson, C.L. and M.J. Rosenblatt, «Coordinating a three-level supply chain with quantity discounts » IIE Transactions, 33/5, 371-385, 2001.

[16] Sobel, M.J. and R.Q. Zhang, «Inventory Policies for Systems with Stochastic and Deterministic Demand» Operation Research, 40/1, 157-162, 2001.

[17] Tirole J., « The theory of industrial organization», MIT Press, Cambridge, MA, 1988.

[18] Tsay, A.A., «The Quantity Flexibility Contract and Supplier-Customer Incentives» Management Science, 45/10, 1339-1358, 1999.

[19] Tsay, A.A., S. Nahmias and N. Agrawal, « Modeling Supply Chain: A Review» Working Paper, Leavey School of Business, Santa Clara University, 1999.

[20] Urban, T.L., «Supply Contracts with Periodic, Stationary Commitment» Production and Operations Management, 9/4, 400-413, 2000.

[21] Wang, Q. et Z. Wu, « Improving a supplier's quantity discount gain from many different buyers» IIE Transactions, 32, 1071-1079, 2000.

[22] Weng, Z.K., « Pricing and Ordering strategies in manufacturing and distribution alliances » IIE Transactions, 29, 681-692, 1997.