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Negotiation-based distributed wood procurement planning within a multi firm environment

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Abstract. Wood procurement planning is a complex task as a multitude of factors must be taken into consideration. It is further complicated in a context of shared procurement areas and co-production, which is typical in the Canadian forest industry. The problem faced by every company's planner is to coordinate and synchronize its own forest operations with those of other companies over several procurement areas. In a multi-firm context, collaboration cannot be taken for granted, and centralization of the decisional power cannot be enforced. A negotiation-based planning and integration approach that takes into account the distributed nature of this planning problem is proposed. The proposed approach results in significant local and global profitability increases when compared to the planning and integration approach currently in use.

Keywords. Wood procurement; forest operations; negotiation; Collaboration; supply chain collaboration.

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INTRODUCTION

Over the years, several models have been proposed to deal with the wood procurement problem. Bettinger and Chung (2004) have put together a literature review of the key contributions and trends in forest-level management planning over the last fifty years. A common feature of most wood procurement models is the use of a centralized approach, although from different point of views. For example, the model presented in Karlsson *et al.* (2004) is used for procurement planning in the perspective of the forest company managing its own forest operations, while Gunnarsson *et al.* (2001) presented a procurement planning model in the perspective of a supplier having to fulfill forest companies' demands.

In a multi-firm context, the procurement problem cannot be tackled with a centralized approach. Although a centralized approach would allow finding the best global solution among the firms, it does not guaranty equity among them. In an effort to treat mills equitably, Wightman and Jordan (1990) propose the use of a uniform unit procurement cost constraint among the firms. This uniformity constraint results in increased global and local costs of several firms by increasing artificially their cost to the level of the most constrained mill. This type of cost increase is unacceptable from the point of view of an independent firm, which goal is to minimize its procurement cost.

Burger (1991) and Burger and Jamnick (1995) worked on harvesting and transportation planning to procure several mills belonging to the same firm. The firm used for the study was divided in independent profit centers. The authors highlight the planning difficulties associated with the presence of several profit centers with locally set (not necessarily coordinated) objectives. Indeed, the woodlands division's goal was to maximize its profit, while the paper mill wanted to minimize its procurement cost. An optimal solution for one is necessarily sub-optimal for the other. A greater internal integration would eliminate this problem by aligning the local objectives towards the firm's profit maximization goal. This centralization of the decision power is possible since the different entities belong to the same organization and thus, can collaborate to achieve a common goal.

In a multi-firm context, collaboration cannot be taken for granted, and centralization of the decisional power cannot be enforced. A firm is indeed interested in its own profitability, regardless of others', which create a paradox that led to the development of supply chain management: a firm's that is solely focus on maximizing its profit, may hinder its partners' performance through uncoordinated decision making, which in turn hold back its own potential profitability.

Weiss (1999) explains that the concept of decentralisation in a planning context is somewhat ambiguous. Indeed, several authors refer to it when talking about the planning activity, while others to characterise the plan's execution. Frayret *et al.* (2004) reviews the main distributed manufacturing paradigms and various forms of interdependence between activities and the coordination mechanism used to manage them. The authors also propose a new classification scheme of coordination. Figure 1 illustrates a class of coordination mechanism referred to as "coordination by plan", which involves the establishment of predefined plans to coordinate *a priori* interdependent activities. The "coordination by plan" class is subdivided into 3 subclasses that can be grouped into various groups. Figure *1-i* and *1-ii* represent the forms of coordination that use a third party support to coordinate their activities. Within the former, the authors distinguish direct supervision (*1-i*) from mediated (*1-ii*) forms of coordination. Figure *1-iii* represents a form of coordination that is directly carried out by mutual adjustment between the centers that execute the activities.

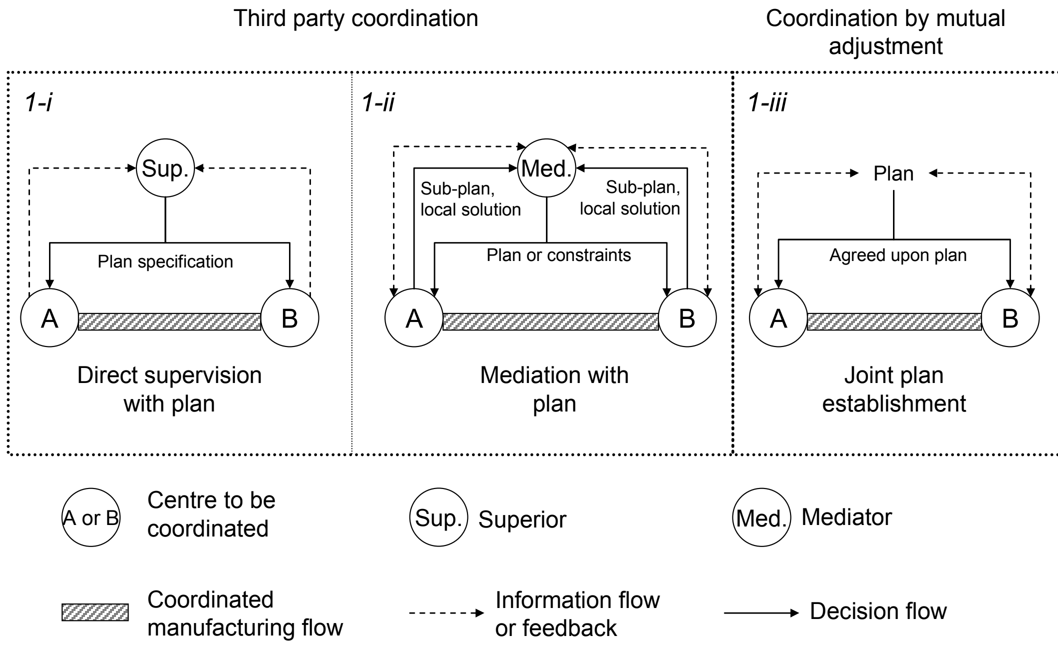

Figure 1. Coordination by plan class of coordination mechanism.

Direct supervision with plan (*1i*) implies that a single center is responsible for planning and coordinating the activities of other centers. These centers just carry out the plan, while they are completely excluded from the planning process. For example, Karlsson *et al.* (2003) solve a wood procurement planning, from a forest company's point of view, including the scheduling of harvest crews. The company plans its procurement and provides a work plan to each of the hired harvest crews.

Mediation with plan (1ii) represents the case where only the coordination activity is centralized. In this case, each center is responsible for developing a partial plan for the activities under its control. Partial plans are submitted to a mediator whose task is to integrate partial plans into a centralized coherent plan. For example, Paredes (1988) proposes an iterative price-guided resource allocation mechanism in large scale forest planning. The central planning authority provides the unit managers with pricing mechanisms that allow them to allocate resources efficiently. Given the solutions provided by each unit, the regional or forest manager determines new prices, solving a problem of maximum social net benefit.

Joint plan establishment (*1iii*) is a system exhibiting no centralization notion. In such a system, each center individually plans its activities in order to achieve its personal goals. Coordination of individual plans is accomplished by the centers without third party involvement.

Direct supervision with plan and *Mediation with plan* are adequate whenever all centers are part of the same group of interest (i.e., they belong to the same firm). The centers in such systems are collaborative. *Joint plan establishment* can be used regardless of the centers' ownership.

Agents and Multi-agent system

A centralized optimization approach cannot account for both local profit maximisation and inter-firm interaction dynamic. A promising approach to tackle this paradox comes from agent technology. The domain of multi-agent systems is an active field of research. Its focus involves the development of distributed information systems in order to design specific collective behaviours emerging from the interactions of several autonomous software agents. The agent paradigm originates from the distributed artificial intelligence domain (DAI). DAI aims at studying and developing multi-agent systems.

Wooldridge and Jennings (1994) defines an agent as a software-based computer system that is autonomous (able to operate without the direct intervention of humans or others, and have some kind of control over its actions and internal state), have a social ability (able to interact with other agents or humans), is reactive (they are able to perceive their environment, and respond in a timely fashion to changes that occur in it), and is pro-active (able to exhibit goal-directed behaviour by taking the initiative). A multi agent system is a decentralized system composed of a set of interacting agents (Weiss 1999). Sandholm (2000) identifies three types of agent: cooperative, self-interested and hostile. Cooperative agents aim at maximizing the sum of the agents' profits. By doing so, an agent is willing to take a loss for the other agents. A self-interested agent wants to maximize its own profit with no interest in others' profits. A hostile agent also aims at maximizing its utility which increases with its own profits but decreases when the others' profit increases.

Agent interactions may be of different nature such as collaboration, coordination and negotiation. A multi agent system may contain more than one type of agent and use different means of interacting. For example, several firms (self-interested agents) must coordinate some of their activities through negotiation. Each firm is made of distinct departments (cooperative agents) collaborating for a common goal.

Gerber and Klusch (2002) present an agent-based integrated services system for timber production and sales. The system supports the main processes that users perform in customer-oriented dynamic timber production and mobile timber trading. It offers its users several integrated commerce techniques for negotiating, communicating, and exchanging information more effectively.

Taking advantage of agent-based characteristics, FOR@C Research Consortium developed an experimental planning platform for the distributed planning of the supply chain of the forest products industry. (Frayret *et al.* 2005). The platform allow to simulate different supply chain configurations and experiment different planning approaches for each of the business units that are present in the supply chain.

Coordination

Malone and Crowston (1994) define coordination as the management of interdependence between activities. Coordination is necessary because of the agent's decision autonomy. The agents' actions must be coordinated, first because of their reciprocal input-output dependence (agents carry out forest operations to provide each other with the species they do not need), also because global constraints must be respected (such as total available volume on a given harvest block), and because none of the agent has enough resources, information or competences to achieve the objectives (i.e., being self-sufficient in terms of procurement).

In a distributed context, the notion of coordination becomes important. Coordination can be achieved through different means according to the agents involved. Non antagonist agents may achieve coordination through collaboration, while self-interested or egoist agents may achieve it through negotiation. Van Brussel *et al.* (1999) define cooperation as a process from which several entities develop mutually acceptable plans and implement them. A largely accepted technique in distributed systems is the Contract-Net protocol (CNP) (Smith 1980). The CNP is an interaction protocol for the cooperative problem solving among agents. It is a high-level protocol for communication among the nodes in a distributed problem solver. Task distribution is affected by a negotiation process, which is a discussion carried on between nodes with tasks to be executed (managers) and nodes that may be able to execute those tasks (contractors). Many extensions have been proposed since it was first introduced. TRACONET (Sandholm's (1993)) extended CNP with a bidding and awarding decision process based on marginal cost calculations based on local agent criteria. Sandholm and Lesser (1995) extended the CNP to self-interested agents. The extension proposed by Aknine (1998) provides for an agent the possibility to apply for several tasks at the same time without running the risk of being penalized in case he breaks the contract. Xu and Weigand (2001) discuss the evolution of the CNP.

Negotiation is a form of interaction often encountered among agents pursuing different objectives. Although several definitions exist in the literature, Jennings' definition (Jennings *et al.* 2001) is the most extensive one. Negotiation is presented as a search within a potential agreement space and summarizes it with three essential points: a negotiation protocol, negotiation objects, and an agents' decision making model. The negotiation protocol defines a set of rules governing the interactions among agents. It identifies the negotiation states, the events triggering the transition from a state to another and possible moves given a certain state. The negotiation objects correspond to the points on which an agreement must be found. Agents negotiate according to the established protocol. The protocol defines the possible actions on the negotiation objects. The decision making model defines an agent's behaviour throughout negotiation. Each agent has its own model which allows him to take position, make concessions and to come to an agreement with others in order to reach his objectives.

The contributions of this paper are (1) a formalisation of firms' procurement interdependence in a context of shared procurement areas and co-production.; (2) a planning and integration approach; (3) a demonstration of the necessity of further intra-firm integration; (4) a demonstration of the potential gains from collaborating by bringing more flexibility into procurement service's transaction price negotiation.

The remainder of this paper is organized as follows; the problem description is presented in the next section, followed by the current planning and inter-firm integration approach. The procurement interdependence among firms is then presented in greater details. Then, the proposed planning and integration approach is introduced. Following this is the experimentation description. Finally, results and concluding remarks are presented.

PROBLEM DESCRIPTION

The problem we consider is one where most of the forested productive land is on public domain. Public land is divided into procurement areas. On each of these areas, Government allocates timber licences (TL) to mills specifying, on a yearly basis, the procurement areas from which a mill can be procured with predefined volumes of one or more tree species. In general, a mill's TL covers more than one procurement area, and several TL may be awarded to different mills (same ownership or not) on the same procurement area, even for the same tree species.

Although a TL does not specify a quality level to the attributed volumes, companies exhibit a definite preference over some, as the quality of the raw material has a direct impact on mill's yield processes and the quality of their manufactured goods. Each procurement area is covered by an annual plan identifying the blocks eligible to be harvested in the upcoming year. Harvesting blocks encompass mixed stands, meaning that whenever a block is harvested, it results in the simultaneous co-production of various resources (e.g., length, species, and diameters). It also means that in a single block, harvested volumes must be sorted according to their characteristics and their ability to be manufactured into certain product types (for example: softwood lumber, hardwood lumber, pulp & paper, and veneer) in order to be delivered to the appropriate mills. Furthermore, the land base is also divided into tariff zones which are used for determining stumpage fees to be paid to the government. These fees depend on the tree species, the quality of the resource and the tariff zone within which it has been harvested. A tariff zone may overlap more than one procurement area and a procurement area may encompass more than a tariff zone. So, several blocks having a same resource will not necessarily have the same stumpage fee associated to it, although they are on the same procurement area. The allocation of specific timber to given mills often results in conflicting situations where more than one company is interested by the same volume.

Even if most companies conduct forest operations, part of their needs must be fulfilled through the purchasing of wood from other companies' operations. Procurement services are traded among firms due to stand composition over the land base and the legislative context within which the companies operate.

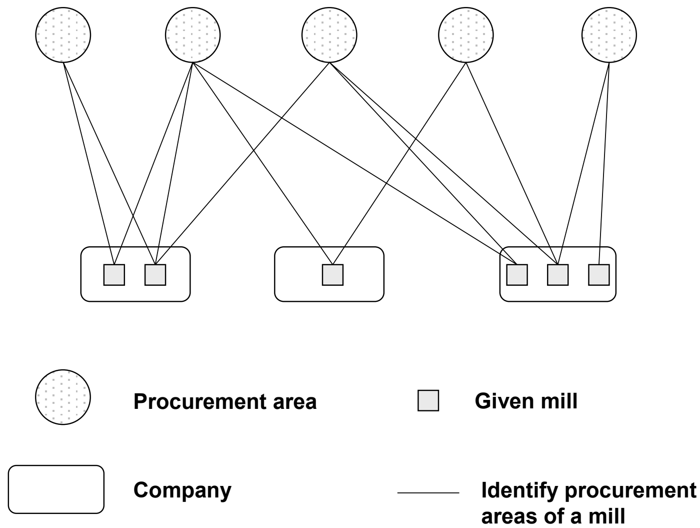

Figure 1. Local and global planning problem.

Figure 1 depicts the planning problem faced by the planners. The problem is twofold: local and global. In order to procure its mills, a company must coordinate its operations on several procurement areas and with those of other companies also involved on several procurement areas.

Since no company has the power to enforce its decisions over others, parties have to agree on the way volumes are to be divided among themselves, on the timing of the procurement activities, wood freshness and on the transaction prices for the procurement services. Timing and coordination of activities are especially important as timber deterioration has a direct impact on processes' costs and yields.

CURRENT PLANNING AND INTEGRATION APPROACH

Due to the inherent complexity of the problem, the planners agreed among themselves to solve the different issues in a successive manner. The current planning and integration approach can be summarized in four successive steps: (1) identification of the companies that will be conducting forest operations on a given procurement area (*the mandated*); (2) allocation of the blocks to be harvested by each of the *mandated*; (3) wood allocation, from the blocks on a given procurement area, among the companies having rights according to their timber licence; and (4) wood procurement activities coordination among the companies. Steps 1 through 3 are accomplished in a meeting held by the interested parties. The inter-firm coordination arises afterward where planners express their preferences in order to plan their respective wood procurement activities. Transaction prices to provide procurement services among them are the main source of conflicts.

In order to perform these tasks, the planners still largely rely on intuition and are without mathematical programming support other then a spreadsheet to try to balance wood delivery to their mills. Planners are faced with the inability to evaluate the quality of their decisions when coordinating their procurement activities within and among their firms.

This paper explores and proposes the basis for decision support system which may assist the planners into planning and coordinating their local procurement plans in a coordinated procurement plan over the shared procurement areas.

PROCUREMENT INTERDEPENDENCE AMONG FIRMS

Instinctively, it is reasonable to think that the revenue one should obtain for its procurement service is equivalent to the cost incurred to provide the service. Although providing timber to each other at cost may sound fair, it may be detrimental to one or more parties involved due to the procurement interdependence among the firms.

Let two firms to be procured from a same block. One of the firms (the *mandated*) is in charge of the procurement activities, from harvesting to delivery for both (the *mandated and the procured*). Several transaction prices are acceptable to the *mandated* and the *procured*, which define their respective range of acceptable average unit price. If these individual ranges overlap, it then defines the price range over which an agreement is possible.

A rational planner will accept to procure its mill(s) from a given harvest block only if he expects to generate a profit from it. In order to perform this assessment, the planner must be able to identify its break even point (BEP), i.e. the average unit price generating null profit. BEP can be seen from two different perspectives. For the *mandated*, the BEP corresponds to the lowest average unit price one is willing to accept as payment for the co-volume harvested on a given block. This price is influenced by the performance of the mandated firm's forest operations and mill's performance, along with the stumpage fees and the market conditions for its products. For the *procured*, the BEP corresponds to the highest average unit price one is willing to pay to be procured with timber originating from a given block. This price is influenced by the mill's performance and the market conditions for its products.

In a given context, the maximum average unit price the *procured* should be willing to pay is a function of the anticipated profit/loss to be generated by the volume procured from the given block, divided by the volume to be received from that block. Similarly, the lowest average unit price the *mandated* should be willing to accept can be extrapolated from the profit/loss he anticipates from the block, divided by the volume to be delivered to the other firms. The anticipated profit is defined by the difference between the anticipated revenues generated by the sale of end products and by-products manufactured with the company's volume originating from the block, and the cost incurred to procure the mills (own and others) with the volume from the block.

In a dynamic context where plans are developed in successive rounds of negotiations, harvesting and processing capacities along with previously negotiated engagements also have an impact on the minimum and maximum acceptable unit prices. Thus,

$$[1]\ L_i = \frac{\left(\text{Profit}_{(\Phi\text{-}1)} - \text{Profit}_{(\Phi)}\right)}{\text{Negotiated volume}}$$

$$[2]\ U_i = \frac{\left(\text{Profit}_{(\Phi)} - \text{Profit}_{(\Phi\text{-}1)}\right)}{\text{Negotiated volume}}$$

where Φ corresponds to a negotiation round.

Equations [1] and [2] correspond to the lower bound (L_i) and upper bound (U_i) of the acceptable average unit price, for the *mandated* and the *procured* respectively, on a given block.

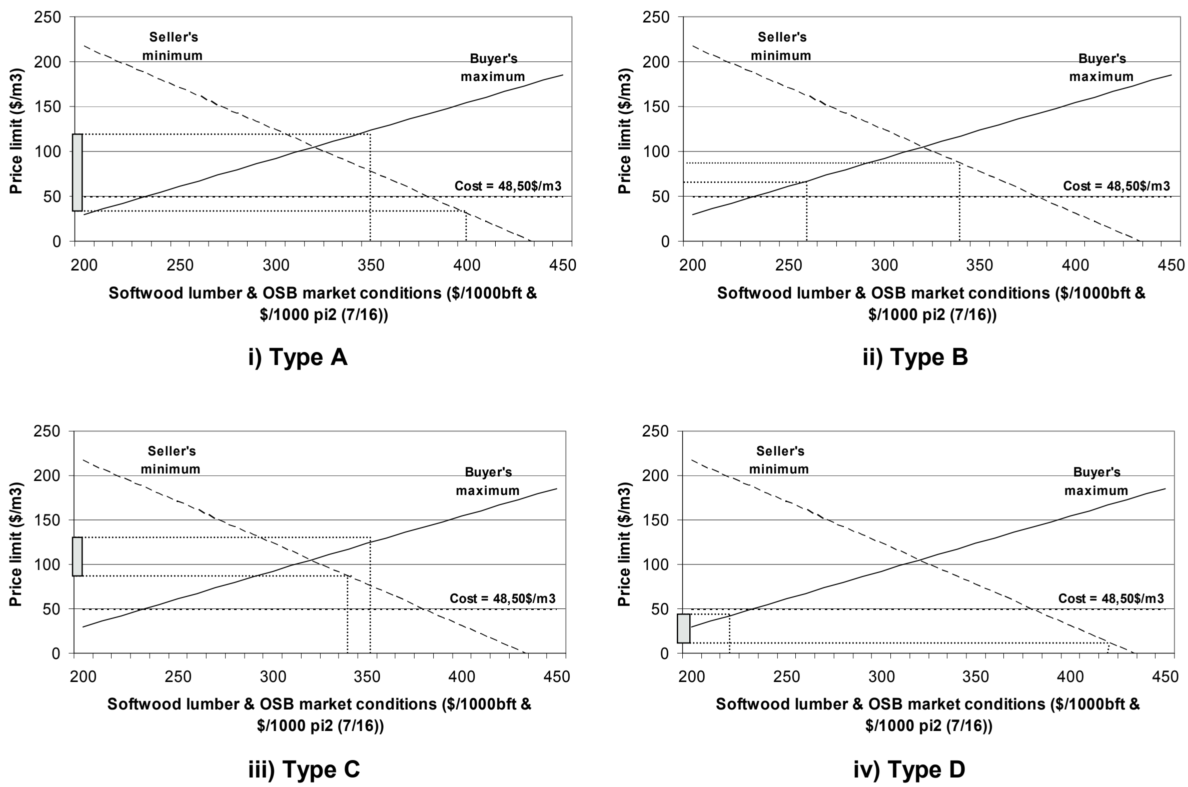

Fig. 2. Types of economic settings.

Figure 2 depicts a static view of the variation in the lower and upper bounds of the acceptable average unit price in relation to market conditions. Graphs i) through iv) illustrates different cases of potential block profitability, given anticipated market conditions for a softwood lumber mill and an oriented strand board mill. For example, graph i) displays market conditions of $400/1000bft for the *mandated* and $350/1000sq.ft(7/16") for the *procured*, which constrains the mutual acceptable average unit price within [29 ; 114]. The presence of a range of potential agreement regarding the unit price does not guaranty that the parties will come to an agreement. In many industrial setting encountered in reality, the negotiation protocol and/or individual negotiation strategies, for example, bring sometimes the negotiation to a dead-lock where none of the parties are willing to compromise, thus resulting in no agreement for the block.

Together, the presence or absence of a range of potential agreement, and the cost of providing the procurement service define the type of economic setting of a block. Figure 2 illustrates the four possible types of economic settings. Types A, C and D are all characterised by the presence of a range of potential agreements. The main difference between these types is related to the relative position of the cost of the procurement service versus the range of potential agreements. Indeed, the procurement service cost sits within, below and above the range of possible agreements respectively for type A, C and D. In the case of type B, there is no range of potential agreement because the lowest acceptable average unit price for the *mandated* is higher than the price the *procured* is willing to pay ($L_i > U_i$).

Together, L_i and U_i define a block's potential profitability ($P = U_i - L_i$), while the agreed upon transaction price (TP) apportions that profitability among the parties ($P_m = TP - L_i$ and $P_p = U_i - TP$ for the *mandated* and the *procured* respectively). Finally, the cost to provide the procurement service is represented by C. From the economic settings illustrated in figure 2, table 1 provides some insight into the opportunity provided by the ability to identify its BEP, and how uncoordinated decision making of one of the parties may hinder one's ability to procure itself.

Without intra-firm coordination, the planner is unable to compute its BEP, thus determining under which conditions a block is economical to harvest. In this context, blocks are harvested and for the sake of equity, $TP = C$ for the volume to be delivered to the *procured*. In the presence of a type A economic setting, both parties generate a profit (P_m = 19 \$/m^3, P_p = 66 \$/m^3) from the block's volume due to good market conditions for their products. In the presence of economic settings of types B and C and D where poor market conditions prevail for at least one of the party, fixing the TP equivalent to C is detrimental to one party, while beneficial to the other.

Table 1. Global and individual profits (\$/m^3) generated by different procurement strategies.

Economic setting			Without intra-firm coordination	With intra-firm coordination	
			$TP = C$	$TP = C$	$TP \neq C$
A	min = 29	**Global**	85	85	85
	max = 114	**Mandated**	19	19	19
	c = 48	**Procured**	66	66	66
B	min = 90	**Global**	-30	0	0
	max = 60	**Mandated**	-42	0	0
	c = 48	**Procured**	12	0	0
C	min = 90	**Global**	40	0	40
	max = 130	**Mandated**	-42	0	0
	c = 48	**Procured**	82	0	40
D	min = 20	**Global**	25	0	25
	max = 45	**Mandated**	28	0	25
	c = 48	**Procured**	-3	0	0

With the ability to evaluate under which conditions a firm's volume from a given block is uneconomical to be harvested, one can choose not to be procured from a given block. This decision has an impact on the other party's ability to be procured. Because many different products are generated in each block, if one of the parties refuses to be procured from a given block, the other parties is unlikely to be able to absorb the extra cost incurred by the co-products. This renders the block uneconomical to the other, although market conditions may be good for its products. Because of this, if parties remain inflexible on the transaction price ($TP = C$), all blocks falling either in type C or D economic settings will be identified as uneconomical by one of the parties and will not be harvested. For example, the type C economic setting corresponds to a situation characterized by poor market conditions for the *mandated* and good conditions for the *procured*. By being inflexible on cost ($TP = C$), the *mandated* would choose not to be procured from the block since it would be unprofitable to him (P_m = -42 \$/m^3). Although the *procured* would generate a profit from its part of the volume (P_p = 82 \$/m^3), his unwillingness to pay more than C deprives him from timber and its related profit (P_p = 0 \$). By accepting to "compensate" the *mandated,* through a financial incentive ($FI \geq 42$ \$/m^3), for the loss the latter would reap by accepting to harvest the unprofitable block, the *procured* would receive its timber and would generate a profit (P_p = 40 \$/m^3). It may be preferable to compromise on transaction price ($TP > C$) by reducing its own share of profitability in order to allow the other to, at least, reach its BEP (P_m = 0 \$), thus rendering the block attractive to both parties. This may make the difference between being procured and not being procured at all. This compensation scheme is also applicable in the case of a type D economic setting, except that this time, the *mandated* "compensates" the *procured* so that the latter agrees to be procured from an unprofitable block.

The procurement interdependence highlighted here is a direct result of the prevailing tenure system and stand composition. The procurement potential of a firm is restricted by the necessary interactions with other firms sharing the same procurement areas.

PROPOSED APPROACH

The procurement problem being inherently distributed due to the presence of financially independent firms, the proposed planning and integration approach adopts the *Joint plan establishment* (Figure *1iii*) coordination mechanism. Figure 2 depicts the proposed approach. It makes use of optimisation and negotiation techniques to develop a coordinated global plan. The first step is for each firm to identify an optimized plan that is the most desirable for it. As firms follow their own interests, the coordination of individual plans is done using a negotiation process based on the passing of inter-firm agreements on the delivery of specific volumes of wood under given conditions. Following the results of the negotiation process in progress, each planner identifies its new most desirable plan given the agreements reached. These new plans are then used to direct the next round of negotiations. Thus, the negotiation process is tightly coupled with the production planning of the firm.

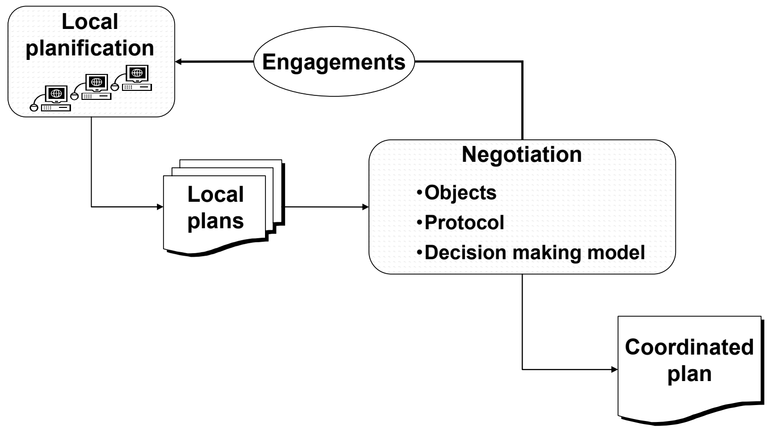

Figure 2. Proposed planning and integration approach.

Intra and inter-firm integration

The negotiation protocol is based on Rubinstein's model of alternating offers (Rubinstein 1982) in which one of the agents makes an offer and the other responds by either accepting the offer, rejecting it or making a counter proposal. If an offer is accepted by all the agents, then the negotiation ends, and this offer is implemented. If one of the agents rejects a proposal, then the negotiation ends and a conflictual outcome results. If no agent has chosen to reject the proposal, but one of the agent judge it to be unsatisfactory in its present form, the negotiation proceeds to round $z + 1$, and the next agent makes a counteroffer, the other agents respond, and so on, until either an agreement or the limit on the number of rounds is reached or the proposal is rejected. When negotiating, the firms may not re-discuss their previous commitments.

The decision making models are based on the tactical wood procurement model presented in Beaudoin *et al.* (to appear). Wood procurement planning anticipates mill processing decisions based on their anticipated market conditions (intra-firm coordination). This anticipation also allows taking into account wood freshness in planning wood flows. Wood freshness refers to time spent between the moment a tree is harvested and its processing through the mill. Mill processing and market conditions anticipation allows identifying the price limit beyond which a block becomes uneconomical for a firm to be procured from. Locally, intra-firm coordination is beneficial because it prevents being procured from uneconomical blocks. By anticipating mill processing and market conditions, it is possible to explore beyond the cost figures and to identify the lowest and highest acceptable unit prices (L_i, U_i) one is willing to be paid or to pay for. Doing so has the potential of increasing the chance to reach an agreement by providing opportunities otherwise unexpected through financial incentive, and therefore increase individual and global profits.

The proposed planning and integration approach respects the distributed nature of the procurement problem on hand. Information is shared through a blackboard. The blackboard represents a shared memory among several agents. Two types of information are shared over the blackboard: 1) Offers and Demands, and 2) available capacities (volume on blocks, harvesting and transport). Offers consist in co-volumes generated from harvesting a block that are rendered available to others by the *mandated*. Demands represent a volume required by the *procured*. Capacity information is shared in order to facilitate a planner's offers and counteroffers generation.

EXPERIMENTATIONS

The goal of the experimentation is to evaluate the proposed planning and integration approach described previously. More precisely, the experimentation aims at evaluating: (1) the potential gain due to a greater intra-firm integration; (2) the potential gain due to a greater inter-firm integration; (3) the potential gain of both, a greater intra and inter-firm integration simultaneously; and (4) the opportunity lost. The latter represents the difference between the combined profitability (P_m+P_p) realized when using the proposed approach and the maximum global profitability that would have been possible to realize in a perfect collaborative environment.

To perform these evaluations, 4 planning and coordinating modes have been used and are described next. The decision making models used by the firms within each planning and coordinating mode are presented in appendix. The models are all derived from the tactical wood procurement planning model presented in Beaudoin *et al.* (to appear).

Planning and coordinating modes

Sequential

This mode correspond to a situation where mill processing capabilities and market conditions are not anticipated (no intra-firm coordination), thus the planner does not have the ability to compute its BEP. In this context, the planner aims at procuring its mill at the lowest possible cost. All the blocks are to be harvested and the volumes to be delivered to the mills. Then, planned deliveries are enforced through constraints in each mill's local revenue maximization problem. Procurement costs are attributed to each mill according to the cost incurred by the procurement activities of their respective volumes ($PT = C$). Finally, local profits (P_m *and* P_p) are derived, for each mill, by subtracting procurement cost from the revenues generated by the sale of products and by-products.

This sequential mode requires three models: a joint centralized wood procurement cost minimization model (*M1*); and two local mill processing revenue maximization models, one for each mill (*M2*). The *sequential* mode is used to mimic the planning and integration approach currently used in the industry, although wood allocation and operation planning decisions are not currently optimized.

Distributed non collaborative

The wood procurement planning and inter-firm coordination is performed in a distributed manner. Local procurement decisions anticipates mill processing decisions based on market conditions. This anticipation allows the planner to compute its BEP and thus to identify unprofitable blocks.

The negotiation objects include: volume, freshness (maximum allowable age of timber) and the time of delivery. In this mode, at least one of the parties remain inflexible on cost, i.e. unwilling to accept less or to pay more than the cost incurred to provide the service ($TP = C$). This mode requires two profit maximization models, one for each mill. Figure 3 illustrates the planning and integrating process among the firms.

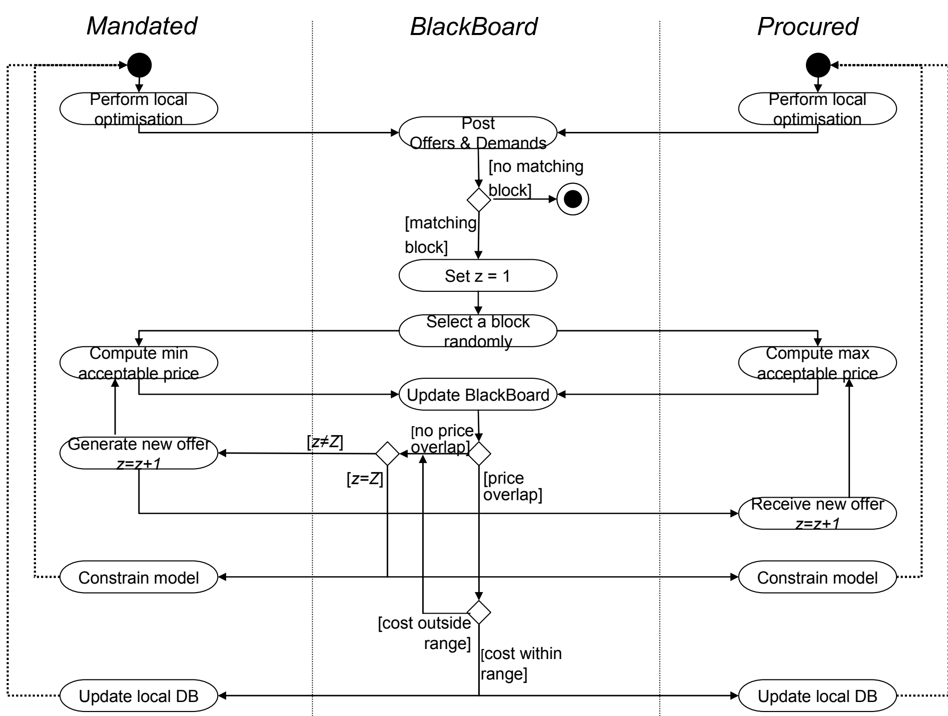

Fig. 3. Activity diagram of the distributed non collaborative mode.

The planning and coordinating process starts with each company performing a local optimization with their local profit maximization model (*M3*). The *mandated* and the *procured* generate a list of offered and desired volumes respectively, which are profitable when the transaction price correspond to the cost of procurement ($TP = C$). The lists are compared in order to find blocks that are offered and demanded at the same time, regardless of the volumes (Type A economic setting). If no block is identified, then the process ends with no possibility to come to an agreement for any blocks, since all of them are unprofitable to at least one of the parties. In the event where more than one blocks is identified, the sequence in which they are to be dealt with is set randomly. Then, a negotiation process is initiated for the selected block and the negotiation round (z) is set to 1. Since all, or a proportion of the volume on the block is offered by the *mandated* and demanded by the *procured*, the offer or the demand generating the lowest procurement cost is to be evaluated. The *mandated* computes the minimum average unit price (L_i) he is willing to accept for the volume under evaluation, while the *procured* computes the maximum average unit price (U_i) he is willing to pay for that same volume. Without an overlap of these acceptable average unit prices, or with an overlap but a procurement cost located outside the mutual acceptable range, the firms cannot come to an agreement for the volume under scrutiny. For each block under investigation, a maximum number of negotiation rounds (Z) is imposed. If no agreement is reached in negotiation round $z = Z$, both parties conclude that they are unlikely to come to an agreement for this block. Both of the local models are constrained to avoid re-evaluating this block. In the case where no agreement is reached in negotiation round $z <= Z$, the *mandated* generates a new offer for the same block in round $z+1$, by modifying one or more negotiation objects. Then, the parties compute respectively L_i and U_i. This loop repeats until both parties come to an agreement or that the parties conclude that they are unlikely to come to an agreement. If an agreement is reached, local databases are updated with the terms of the agreement, and local optimizations are performed to account for the new development. These updated local solutions are then used by the planners to orient the subsequent negotiations. The *mandated* and the *procured* generate a list of offered and desired volumes respectively. The planning and coordinating process keeps going as long as blocks that are offered and demanded at the same time can be identified by comparing the lists.

Distributed collaborative

As in the previous mode, the wood procurement planning and inter-firm coordination is performed in a distributed manner, and local procurement decisions anticipates mill processing decisions based on market conditions. The negotiation objects include: volume, freshness (maximum age of timber), the time of delivery and the transaction price. In this mode, both parties collaborate by showing greater flexibility on cost through financial incentives ($TP \neq C$), as long as it allows them to increase their local profits. This mode requires two profit maximization models (*M3*), one for each mill. Figure 4 illustrates the planning and coordinating process among the firms.

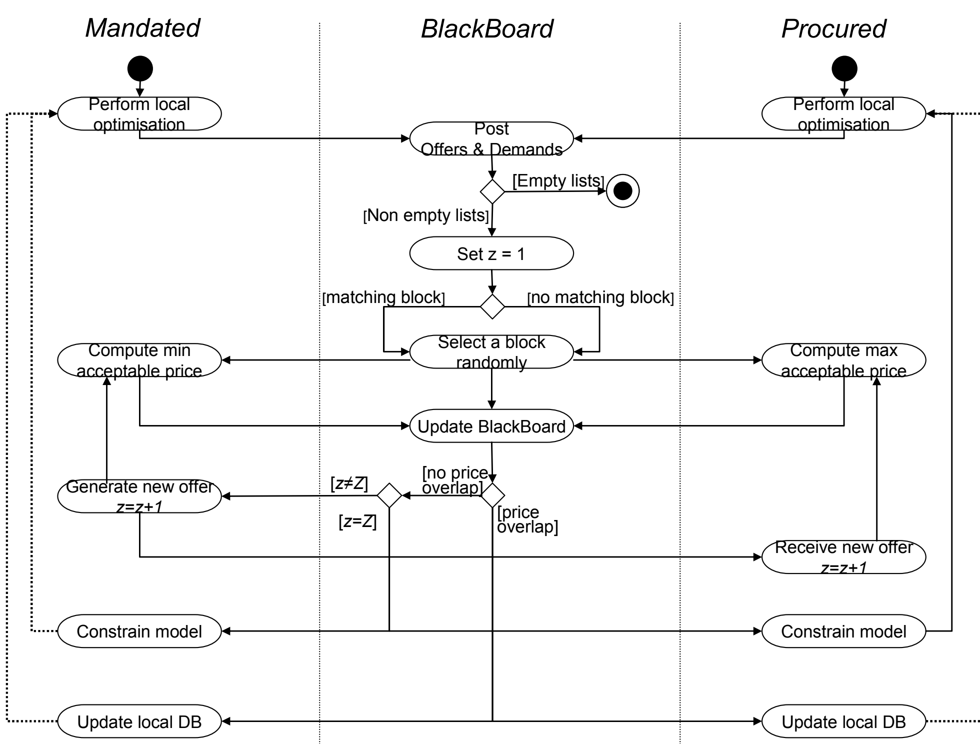

Fig. 4. Activity diagram of the distributed collaborative mode

The negotiation process is similar to the one used in the *distributed non collaborative* mode, except for the propositions to be evaluated and the acceptability criteria of a proposition being evaluated.

All blocks being the subject either of an offer from the *mandated* or a demand from the *procured* will be investigated. The blocks that do not show up on either list will be ignored since they are not profitable to both parties (Type B economic setting). The planning and inter-firm coordinating process deals first with the blocks being offered and requested at the same time (Type A economic setting). It then addresses the blocks that are profitable to one of the parties (Type C and D economic settings). The process ends when neither offer nor demand remain on the lists.

We recognize that the presence of a mutual acceptable average unit price does not guaranties that parties would come to an agreement, since the translation of a proposition into an agreement depends, among others, on each parties' negotiation strategy. Testing the performance of different negotiation strategies to evaluate how each performs when confronted with others is beyond the scope of this paper. As mentioned previously, L_i and U_i define a block's profitability while *TP* apportions it among the parties. In order to evaluate the potential benefits of collaboration, an agreement was systematically concluded whenever $U_i > L_i$, and *TP* was assumed to equally divide block profitability among the parties.

Centralized

The wood procurement planning and inter-firm coordination is performed in a centralized manner, as if all the mills to be procured would belong to the same company. The procurement decisions anticipate mills' processing decisions based on their respective market conditions. This mode requires one profit maximization model (*M4*). The centralized mode permits to identify the maximum global profit that can be generated from the blocks to be harvested.

Evaluation

The evaluation of the proposed approach is performed through benchmarking the results achieved with the different planning and inter-firm coordinating modes.

For the experiment, 40 scenarios of market conditions have been generated based on historical data. Within each scenario, market conditions for softwood lumber and oriented strand board are identified. Each of the 40 scenarios is run through the 4 different planning and inter-firm coordinating modes, which resulted in 160 tests. Profitability results achieved through the experimentations are then used for comparisons. Table 2 identifies the planning and inter-firm coordinating modes being benchmarked and the information revealed by the observed differences.

Table 2. Benchmarking information

Benchmarking		Information
Sequential	Distributed non collaborative	Potential gain/loss from greater intra-firm coordination
Distributed non collaborative	Distributed collaborative	Potential gain/loss from greater inter-firm coordination
Sequential	Distributed collaborative	Potential gain/loss from both intra and inter-firm coordination
Distributed collaborative	Centralized	Opportunity loss

The test problem used in performing the evaluation considered two firms. One of the firms is the *mandated*, while the other is the *procured*. Thus, the firm responsible for conducting forest operations and the wood allocation among the mills are known. Each firm owns a mill (softwood lumber and oriented-strand board) holding a timber licence on the considered procurement area. The procurement area encompasses 5 eligible blocks for harvesting. Each block holds a specific volume and composition of resources. 2 different resources are considered, each belonging to one of 2 tree species present. The planning horizon covers 4 periods. Also, 4 different ages are considered to represent the fibre freshness, which have been grouped within 2 age classes. Furthermore, 2 valuation levels are considered for each age class in a market anticipation function.

RESULTS AND DISCUSSION

This section presents the results obtained from comparing profitability levels achieved by the four procurement planning and inter-firm coordination modes. Benchmarking results are reported per type of economic setting. Economic settings were defined on a per block basis. Since the test problem incorporates several blocks to be planned and coordinated, the results of a given scenario have been attributed to the type of economic setting representing the majority of the volumes to be planned and coordinated under that scenario.

Sequential – Distributed non collaborative

Benchmarking results between the *sequential* and the *distributed non collaborative* modes provides information on the potential gain/loss due to a greater intra-firm coordination (Table 3).

Table 3. Sequential - Distributed non collaborative benchmarking

Type of economic setting	Gains/loss ('1,000$)					
	Average			Standard deviation		
	Mandated	*Procured*	Global	*Mandated*	*Procured*	Global
A	-47	-12	-59	89	86	95
B	134	18	152	81	27	103
C	113	-136	-23	75	193	144
D	-191	60	-131	253	23	258

Three different situations are observed: (1) both parties witness a decrease in profitability; (2) both parties increase their profits; and (3) only one of the party increases its profit, while the other observe a decrease in profit.

In the type A economic setting, both parties witness a decrease in profitability. In type A setting, blocks are profitable to both parties at current and/or anticipated market conditions. The counter performance of the *distributed non collaborative* planning and coordinating mode can be explained by the way blocks are scheduled. Indeed, this mode attempts block scheduling in a random successive, one at a time manner (Figure 3). This means that once parties come to an agreement, they have to pursue the negotiations without the chance to seek compromises between the blocks. This inability to account for block profitability tradeoffs translates into lost opportunity. Also, this inability to account for block compromise may render some potentially profitable volumes undesirable due to temporal constraints imposed by previous agreement. Each time an agreement is reached, some production capacity (harvesting and milling) is tied to it. Even if the volume of a block would be profitable at current or anticipated market conditions, the firm may be unable to realise this profit because of a lack of production capacity, thus resulting in no agreement for the volume under scrutiny. Table 4 presents the percentage of the timber licences that is delivered to both mills.

Table 4. Average timber licences fulfilement

Type of economic setting	Average timber licence fulfilement (%)			
	Sequential		Distributed non collaborative	
	Mandated	*Procured*	*Mandated*	*Procured*
A	100	100	37	52
B	100	100	2	8
C	100	100	10	25
D	100	100	1	5

An advantage of the *distributed non collaborative* mode is that it allows identifying blocks that are locally unprofitable and to postpone harvesting as reported by the reduction in timber licences fulfilment (Table 4). Both parties gain from postponing harvesting of Type B blocks. Meanwhile, this approach also prevents harvesting type C and Type D, since blocks are unprofitable to one of the parties, which is detrimental to one while beneficial to the other. The impact on profitability is directly linked to the proportion of the total volume within each type of economic setting (A,B,C and D). As described previously, the *mandated* expects generating a loss from the volume on type B and C, and a profit from type A and D blocks. The *mandated* will increase its profit if the gain from not harvesting blocks of type B and C offsets the loss incurred by not harvesting block of type D. Similarly, the *procured* expects generating a loss from the volume on type B and D, and a profit from type A and C blocks. The *procured* will thus increase its profit if the gain from not harvesting blocks of type B and D offsets the loss incurred by not harvesting block of type C.

In a *distributed non collaborative* mode, only Type A blocks will be harvested. In all cases, timber licences fulfillment is equal to or less than in the s*equential* mode which harvests 100% of the allocated volumes. The reduction in timber licences fulfillment is attributable to the procurement interdependence of the firms.

Distributed non collaborative – Distributed collaborative

Benchmarking results between the *distributed non collaborative* and the *distributed collaborative* modes provides information on the potential gain/loss due to a greater inter-firm coordination (Table 5).

Table 5. Distributed non collaborative – distributed collaborative benchmarking

Type of economic setting	Gains/loss ('1,000$)					
	Average			Standard deviation		
	Mandated	*Procured*	Global	*Mandated*	*Procured*	Global
A	34	0,4	34,4	56	95	56
B	2	1	3	1	2	3
C	54	32	86	59	71	129
D	990	52	142	132	72	195

The *distributed collaborative* mode uses financial incentives in order to seek agreements for the volumes on blocks that are unprofitable to one of the parties. Although Table 5 reports profitability improvements for both parties, the potential gains from the distributed collaborative mode is best seen from the global perspective. As reported earlier, the local gains observed are influenced by the negotiation protocol and local negotiation strategies. In the experiment, a block's profitability was equally divided among the firms

.Through collaboration, wealth creation can be increased. This increase is directly attributed to a higher timber licence fulfilment. In the case of the *distributed non collaborative* mode, parties were unwilling to pay more or to be paid less than the cost incurred by the procurement activities. Doing so resulted into harvesting only the blocks being profitable to both parties (Type A). Meanwhile by accepting to collaborate through financial incentives, a block that is not profitable to one of the player may become profitable to both and be harvested, thus contributing to both parties' local profits. Table 6 shows the increase in timber licence fulfillment resulting from increase collaboration. Increases in timber licences fulfilment have been observed for every types of economic settings.

Tableau 6. Average timber licences fulfilment

Type of economic setting	Average timber licence fulfilement (%)			
	Distributed non collaborative		Distributed collaborative	
	Mandated	*Procured*	*Mandated*	*Procured*
A	37	52	70	77
B	2	8	5	24
C	10	25	44	68
D	1	5	41	46

Although collaboration allows increasing local and global profitability, the use of financial incentives represent an added cost to the wood procurement problem for firms sharing procurement areas.

Sequential – Distributed collaborative

Benchmarking results between the *sequential* and the *distributed collaborative* modes provides information on the potential gain/loss due to both, greater intra and inter-firm coordination (table 7). This benchmarking compares the proposed approach to the one currently in use.

Tableau 7. Sequential – Distributed collaborative benchmarking

Type of economic setting	Gains/loss ('1,000$)					
	Average			Standard deviation		
	Mandated	*Procured*	Global	*Mandated*	*Procured*	Global
A	-13	-11	-24	123	169	86
B	136	19	155	80	26	102
C	167	-104	63	121	123	42
D	-101	112	11	136	72	70

Again, the potential gains from the *distributed collaborative* mode is best seen from the global perspective. Gains in profitability are observed for every economic setting except for type A. This counter performance of the *distributed collaborative* planning and coordinating mode can be attributed to the way blocks are being planned, in a random successive, one at a time manner (Figure 4). A negotiation protocol authorizing the renegotiation of previous agreements could allow find solutions increasing local profits.

The experiment also revealed that the worst the current or anticipated market conditions are, the greater the potential gains are. This reflects the importance of having the ability to identify locally unprofitable blocks through intra-firm coordination. From tables 4 and 6, a reduction in timber licences fulfilment can be noticed for every types of economic setting.

Distributed collaborative – Centralized

Benchmarking results between the *distributed collaborative* and the *centralized* modes provides information on the opportunity loss, i.e. the difference between the maximum profits that would have been possible to generate and the realized profits through the proposed approach.

Table 8 highlights the observed global profit gap between the *distributed collaborative* and the *centralized* planning and coordinating modes.

Table 8. Distributed collaborative – Centralized benchmarking

Type of economic setting	Opportunity loss ('1,000$)					
	Average			Standard deviation		
	Mandated	*Procured*	Global	*Mandated*	*Procured*	Global
A	-26	-35	-61	115	162	75
B	1	-3	-2	3	4	2
C	92	-98	-6	122	122	9
D	-100	68	-32	133	89	44

Opportunity losses are encountered for every types of economic setting. The better the current or anticipated market conditions are, the higher the opportunity loss is.

The gap between the *distributed collaborative mode* and the *centralized mode* could be reduced by modifying the negotiation protocol to authorize decommiting from previously agreed contracts. Sandholm (2000) presents a new contract type called leveled commitment contract. A mechanism is built into the contract that allows unilateral decommitting at any point in time. This is achieved by specifying in the contract decommitment penalties, one for each of the agent.

CONCLUSIONS AND FUTUR WORK

This paper explored the firms' procurement interdependence in a context characterised by shared procurement areas, mixed stands and heterogeneous economic settings. Through experimentations, we looked at how different planning and coordinating modes perform, both from the individual firm's point of view and globally.

First, we showed the advantage of locally anticipating mill processing based on anticipated market conditions. Locally, this anticipation allows identifying blocks that are uneconomical in the current or anticipated market conditions. Indeed, as soon as a firm refuse to be procured from a given block, another firm interested in the co-volume is unlikely to be able to support all of the costs on its own. Consequently, a firm would chose not to be procured due to the added cost. We then showed the advantage of inter firm collaboration in bringing more flexibility on transaction price negotiation for the provided procurement services. Inter-firm collaboration through financial incentives can make blocks economically viable to both parties, which, in turn, improves timber licence fulfillment and increases local profits for both parties. These financial incentives constitute a hidden integration cost inherent to the procurement context under investigation.

There are a number of ways in which the *distributed collaborative* planning and coordinating mode introduced in this paper can be improved in order to reduce the opportunity loss and the integration cost. Firstly, as reported, allowing decommitting from previous engagements to allow for inter-block compromises and experimenting different negotiation protocols and strategies could permit creating greater wealth among the same set of blocks. Also, extending this work to include other firms (softwood lumber, hardwood lumber, pulp & paper, veneer) on a same procurement area will bring other decisional variables. The latter would be such as which company(ies) is(are) in charge of the procurement activities on each block, and wood allocation among the firms since more than one have rights for the same resource. These added decisional variables would draw a more complete picture of the wood procurement problem.

Finally, extending the experiment to integrate several firms being procured from several procurement areas is expected to bring more insight into firms' wood procurement interdependence. With the insight gained from the latter, it could be possible to improve the timber licences attribution among the mills. It could be possible to find the best possible match among mills (products) sharing the same procurement areas in order to reduce the integration cost (financial incentives) discussed above.

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APPENDIX

This appendix presents the models (*M1* to *M4*) that have been used in order to conduct the experiments. All models are derived from the tactical wood procurement planning model presented in Beaudoin *et al.* (to appear). Data sets are first introduced, followed by the parameters and variables used to formulate the model. Finally the mathematical formulations are presented and described.

Sets

A	: set of possible ages of the harvested timber
C	: set of age classes
I	: set of blocks
K	: set of procurement area
N	: set of valuation levels
R	: set of resources
S	: set of tree species
T	: set of periods
U, U'	: set of mills under a company's ownership and others' respectively
$I_{(k)}$	: set of blocks on procurement area *k*
$I_{(Ku)}, I_{(Ku')}$	: set of blocks on the procurement areas identified on mill *u* and *u'* timber license respectively
$K_{(u)}$	: set of procurement areas identified on mill *u* TL
$R_{(s)}$	: set of resources belonging to the same tree species
$R_{(u)}, R_{(u')}$	: set of resources desirable for mill *u* and *u'* respectively

Parameters

b_t^H	: harvest capacity during period *t*
b_t^T	: transport capacity during period *t*
b_{ut}^P	: processing capacity at mill *u* during period *t*
b_{ut}^S	: log yard storing 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*
$c_{riut}^T, c_{riu't}^T$	: unit cost to transport resource *r* from block *i* to mill *u*, or *u'*

respectively, during period t

c^{logs}_{riuat} : unit cost to buy resource r of age a from block i to be delivered to mill u during period t

$c^{exp\,logs}_{riuat}$: expected unit cost to buy resource r of age a from block i to be delivered to mill u during period t

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

$d^{byproduct}_{sa_u^{\max}ut}$: demand for by-products of tree species s of a maximum age of $a_u^{\max}$ at mill u during period t

$d^{logs}_{ra_{u'}^{\max}u't}$: demand for logs of resource r of a maximum age of $a_u^{\max}$ from mill u' during period t

f_{rit} : stumpage fee for resource r on block i during period t

g^{market}_{rucnt} : average unit revenue net of processing cost for end products manufactured from resource r within age class c at mill u and sold at valuation level n during period t

$g^{byproduct}_{sut}$: unit revenue from the sale of chips of resource type s at mill u during period t

$g^{exp\,logs}_{riu'at}$: expected log revenue for resource r of block i of age a to be delivered to mill u' during period t

$g^{logs}_{riu'a_{u'}^{\max}t}$: log revenue for resource r of block i of a maximum age $a_{u'}^{\max}$ to be delivered to mill u' during period t

I^{F}_{rai0} : volume of resource r of age a stored on block i at the beginning of the planning horizon

I^{U}_{rai0} : volume of resource r of age a stored at mill u at the beginning of the planning horizon

l_i : maximum number of period over which harvesting can occur in block i

n_i : maximum number of blocks in which harvesting can occur during period t

v_{ri} : volume of resource r on block i

v_{suk} : maximum volume or tree species s that can be delivered to mill u from procurement area k

$v^{\max}_{rucnt}$: 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_{raiut} : volume of resource r of age a to be received at mill u from block i during period t

α_{rau} : end products' average yield from processing resource r of age a through mill u

γ_{rau} : chips average yield from processing resource r of age a through mill u

Decision variables

X_{it}	: proportion of block *i* harvested during period *t*
H_{it}	: $\begin{cases} 1, \text{if harvesting occurs on block } i \text{ during time period } t \\ 0, \text{otherwise} \end{cases}$
I^F_{rait}	: volume of resource *r* of age *a* stored on block *i* during period *t*
I^U_{raut}	: volume of resource *r* of age *a* stored at mill *u* during period *t*
$S_{raiu't}$	: 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 products manufactured from resource *r* of age *a* that is sold by mill *u* at valuation level *n* during period *t*
M_{raut}	: volume of resource *r* of age *a* processed through mill *u* during period *t*
V^O_{riat}	: volume of resource *r* of age *a* from block *i* offered to others during period *t*
V^D_{riuat}	: volume of resource *r* from block *i* demanded by mill *u* of a maximum age of $a_u^{\max}$ during period *t*

Models

Model M1- Joint centralized wood procurement cost minimization model

Minimize:

[1]
$$\sum_{i\in I}\sum_{t\in T}\left(c^{\mathrm{H}}_{it}X_{it}\sum_{r\in R}v_{ri}\right) + \sum_{r\in R}\sum_{i\in I}\sum_{t\in T}v_{ri}f_{rit}X_{it} + \sum_{u\in U}\sum_{i\in I_{(Ku)}}\sum_{r\in R_{(u)}}\sum_{t\in T}\left(c^{\mathrm{T}}_{riut}\sum_{a\in A}Y_{raiut}\right) + \sum_{r\in R}\sum_{i\in I}\sum_{t\in T}\left(c^{\mathrm{S}}_{rit}\sum_{a\in A}I^{\mathrm{F}}_{rait}\right)$$

Subject To:

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

[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] $$\sum_{r \in R_{(u)} \cap R_{(s)}} \sum_{a \in A} \sum_{i \in I_{(k)}} \sum_{t \in T} Y_{raiut} \quad \leq \quad v_{suk} \quad \forall s \in S, \forall u \in U, \forall k \in K_{(u)}$$

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

[8] $$\sum_{a \in A} \sum_{u \in U} \sum_{r \in R_{(u)}} \sum_{i \in I_{(Ku)}} Y_{raiut} \quad \leq \quad b_t^{\mathrm{T}} \quad \forall t \in T$$

[9] $$\sum_{a \in A} \sum_{u \in U} \sum_{t \in T} Y_{raiut} \quad = \quad v_{ri} \quad \forall r \in R, \forall i \in I$$

[10.1]

[10.2]

[10.3]

$$I_{rait}^{\mathrm{F}} = \begin{cases} v_{ri} X_{it} - \sum_{u \in U} Y_{raiut} & \forall r \in R, \forall i \in I, \forall t \in T, a = 1 \\ I_{r(a-1)i(t-1)}^{\mathrm{F}} - \sum_{u \in U} Y_{raiut} & \forall r \in R, \forall i \in I, \forall t \geq 2, \forall a \geq 2 \\ I_{rai0}^{\mathrm{F}} - \sum_{u \in U} Y_{raiut} & \forall r \in R, \forall i \in I, t = 1, \forall a \geq 2 \end{cases}$$

[11] $$X_{it}, I_{rait}^{\mathrm{F}} \quad \geq \quad 0 \quad \forall r \in R, \forall a \in A, \forall i \in I, \forall t \in T$$

[12] $$Y_{raiut} \quad \geq \quad 0 \quad \forall u \in U, \forall r \in R_{(u)}, \forall a \in A, \forall i \in I_{(Ku)}, \forall t \in T$$

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

The four terms of the objective function (Equation [1]) represent respectively the harvesting, stumpage, transporting and roadside storing costs. Equations [2] and [9] ensure that all the available volumes to fulfill the timber licence are planned to be harvested and delivered to the mills. Equations [3] through [5] are used in order to avoid excessive equipment transportation needs. Equation [3] assigns a value to the binary variables when a block is harvested, while [4] and [5] limit respectively the number of periods over which a block may be harvested and the number of blocks that can be harvested in any period. Equation [6] enforces the limits imposed by the timber licence. Equations [7] and [8] represent respectively the harvesting and transportations capacities. Finally, equations [10.1] through [10.3] represent flow conservation constraints.

Model M2 – Local mill processing revenue maximization model.

Maximize:

[14]
$$\sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{c\in C}\sum_{n\in N}\sum_{t\in T}\left(g_{rucnt}^{\text{market}}\sum_{a_c^-}^{a_c^+}D_{raunt}\right) + \sum_{s\in S}\sum_{u\in U}\sum_{t\in T}\left(g_{sut}^{\text{byproducts}}\sum_{r\in R_{(s)}}\sum_{a\in A}\left(\gamma_{rau}M_{raut}\right)\right)$$
$$-\sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{t\in T}\left(c_{rut}^{\text{S}}\sum_{a\in A}I_{raut}^{\text{U}}\right)$$

Subject To:

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

[16.1] [16.2] [16.3]
$$I_{raut}^{\text{U}} = \begin{cases} \sum_{i\in I_{(Ku)}}w_{raiut} - M_{raut} & \forall u\in U, \forall r\in R_{(u)}, \forall t\in T, a=1 \\ I_{r(a-1)u(t-1)}^{\text{U}} + \sum_{i\in I_{(Ku)}}w_{raiut} - M_{raut} & \forall u\in U, \forall r\in R_{(u)}, \forall t\ge 2, \forall a\ge 2 \\ I_{rau0}^{\text{U}} + \sum_{i\in I_{(Ku)}}w_{raiut} - M_{raut} & \forall u\in U, \forall r\in R_{(u)}, t=1, \forall a\ge 2 \end{cases}$$

[17] $$\sum_{r\in R_{(u)}}\sum_{a\in A}I_{raut}^{\text{U}} \le b_{ut}^{\text{S}} \quad \forall u\in U, \forall t\in T$$

[18] $$\sum_{a\in A}I_{raut}^{\text{U}} \ge b_{rut}^{\min} \quad \forall u\in U, \forall r\in R_{(u)}, \forall t\in T$$

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

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

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

[22] $$I^{\text{U}}_{raut}, M_{raut}, D_{raunt} \geq 0 \quad \forall u\in U, \forall r\in R_{(u)}, \forall a\in A, \forall n\in N, \forall t\in T$$

The three terms of the objective function (Equation [14]) represent respectively the revenues from the sale of end products and chips on the market and log yard storing cost. Individual mill processing and log yard storing capacities are represented by equations [15] and [17]. Log deliveries obtained from model *M1* are enforced through the flow conservation equations [16.1] through [16.3] by the parameter w_{raiut}. Equation [18] set the level of safety stock to maintain at the mill, while end products market conditions are modeled through equation [19]. Log and chips demands are satisfied through equations [20] and [21].

Model M3- Local profit maximization model.

Maximize:

[24] $$\begin{aligned}
&\sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{c\in C}\sum_{n\in N}\sum_{t\in T}\left(g^{\text{market}}_{rucnt}\sum_{a_c^-}^{a_c^+}D_{raunt}\right) + \sum_{s\in S}\sum_{u\in U}\sum_{t\in T}\left(g^{\text{byproducts}}_{sut}\sum_{r\in R_{(s)}}\sum_{a\in A}(\gamma_{rau}M_{raut})\right)\\
&+\sum_{u'\in U'}\sum_{r\in R_{(u')}}\sum_{a_{u'}^{\max}\in A}\sum_{t\in T}\left(d^{\text{logs}}_{ra_{u'}^{\max}u't}\sum_{i\in I\cap I_{(Ku')}}g^{\text{logs}}_{riu'a_{u'}^{\max}t}\right) + \sum_{r\in R_{(u')}}\sum_{i\in I\cap I_{(Ku')}}\sum_{a\in A}\sum_{t\in T}\left(V^{\text{O}}_{riat}\sum_{u'\in U'}g^{\text{exp logs}}_{riu'a_{u'}^{\max}t}\right)\\
&-\sum_{i\in I}\sum_{t\in T}\left(c^{\text{H}}_{it}X_{it}\sum_{r\in R}v_{ri}\right) - \sum_{r\in R}\sum_{i\in I}\sum_{t\in T}v_{ri}f_{rit}X_{it}\\
&-\sum_{i\in I_{(Ku)}}\sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{t\in T}\left(c^{\text{T}}_{riut}\sum_{a\in A}Y_{raiut}\right) - \sum_{u'\in U'}\sum_{r\in R_{(u')}}\sum_{i\in I\cap I_{(Ku')}}\sum_{t\in T}\left(c^{\text{T}}_{riu't}\sum_{a\in A}S_{raiu't}\right)\\
&-\sum_{r\in R}\sum_{i\in I}\sum_{t\in T}\left(c^{\text{S}}_{rit}\sum_{a\in A}I^{\text{F}}_{rait}\right) - \sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{t\in T}\left(c^{\text{S}}_{rut}\sum_{a\in A}I^{\text{U}}_{raut}\right)\\
&-\sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{i\in I_{(Ku)}}\sum_{a\in A}\sum_{t\in T}c^{\text{logs}}_{riuat}w_{riuat} - \sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{i\in I_{(Ku)}}\sum_{a\in A}\sum_{t\in T}c^{\text{exp logs}}_{riuat}V^{\text{D}}_{riuat}
\end{aligned}$$

Subject to:

[3]- [5], [7], [15], [17]-[21]

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

[26] $$\sum_{a\in A}\sum_{t\in T}\left(\sum_{u\in U}\left(Y_{raiut} + w_{riuat} + V^{\mathrm{D}}_{riuat}\right) + \sum_{u'\in U'} S_{raiu't}\right) \leq v_{ri} \quad \forall r \in R, \forall i \in I$$

[27] $$\sum_{r\in R_{(u)}\cap R_{(s)}}\ \sum_{a\in A}\sum_{i\in I_{(k)}}\sum_{t\in T}\left(Y_{raiut} + w_{riuat} + V^{\mathrm{D}}_{riuat}\right) \leq v_{suk} \quad \forall s \in S, \forall u \in U, \forall k \in K_{(u)}$$

[28] $$\sum_{a\in A}\sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{i\in I_{(Ku)}} Y_{raiut} + \sum_{a\in A}\sum_{u'\in U'}\sum_{r\in R_{(u')}}\sum_{i\in I\cap I_{(Ku')}} S_{raiu't} \leq b^{T}_{t} \quad \forall t \in T$$

[29.1]
[29.2]
[29.3]
$$I^{\mathrm{F}}_{rait} = \begin{cases} v_{ri}X_{it} - \sum_{u\in U} Y_{raiut} - \sum_{u'\in U'} S_{raiu't} - V^{\mathrm{o}}_{riat} & \forall r \in R, \forall i \in I, \forall t \in T, a = 1 \\ I^{\mathrm{F}}_{r(a-1)i(t-1)} - \sum_{u\in U} Y_{raiut} - \sum_{u'\in U'} S_{raiu't} - V^{\mathrm{o}}_{riat} & \forall r \in R, \forall i \in I, \forall t \geq 2, \forall a \geq 2 \\ I^{\mathrm{F}}_{rai0} - \sum_{u\in U} Y_{raiut} - \sum_{u'\in U'} S_{raiu't} - V^{\mathrm{o}}_{riat} & \forall r \in R, \forall i \in I, t = 1, \forall a \geq 2 \end{cases}$$

[30.1]
[30.2]
[30.3]
$$I^{\mathrm{U}}_{raut} = \begin{cases} \sum_{i\in I_{(Ku)}}\left(Y_{raiut} + w_{riuat} + V^{\mathrm{D}}_{riuat}\right) - M_{raut} & \forall u \in U, \forall r \in R_{(u)}, \forall t \in T, a = 1 \\ I^{\mathrm{U}}_{r(a-1)u(t-1)} + \sum_{i\in I_{(Ku)}}\left(Y_{raiut} + w_{riuat} + V^{\mathrm{D}}_{riuat}\right) - M_{raut} & \forall u \in U, \forall r \in R_{(u)}, \forall t \geq 2, \forall a \geq 2 \\ I^{\mathrm{U}}_{rau0} + \sum_{i\in I_{(Ku)}}\left(Y_{raiut} + w_{riuat} + V^{\mathrm{D}}_{riuat}\right) - M_{raut} & \forall u \in U, \forall r \in R_{(u)}, t = 1, \forall a \geq 2 \end{cases}$$

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

[32] $$X_{it}, I^{F}_{rait}, V^{o}_{riat} \geq 0 \quad \forall r \in R, \forall a \in A, \forall i \in I, \forall t \in T$$

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

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

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

The objective function accounts for revenues and costs. The first and second term represents the revenues from the sales of end products and chips. The third term account for revenues from the sales of logs to other firms for which an agreement has been reached. The fourth term represents the expected revenues from the sales of logs. Whenever a block is profitable for the *mandated* by selling logs at their cost, the firm will offer these volumes to the other firms (V^{o}_{riat}). The costs accounted for include harvesting and stumpage, transport to own and others' mills, and storing (roadside and mill yard). The last two terms accounts respectively for the cost to buy logs from other firms under the terms of an agreement and the expected cost to buy logs. Equation [25] ensures that harvested volumes on every block do not exceed availability. Equation [26] ensures that the volumes to be received, from own and others' operations, and the desired volume from a given block do not exceed availability. Equation [27] enforces the limits imposed by a mill's timber licence by accounting for both, the volumes to be received (own and others' operations) and the desired volumes for the mill. Transport capacity (eq. [28]) accounts for transport to own and others' mills. Flow conservation equations [29.1]-[29.3] differentiate between transport to own mills and to others', and withdraw offered volumes from computed end of period inventory. Flow conservation equations [30.1]-[30.3] accounts for volumes to be received through own and others' operations and desired volumes. Equation [31] ensures that log demands, for which an agreement has been reached, are satisfied.

Model M4 – Joint centralized wood procurement profit maximization model.

Maximize:

$$
\begin{aligned}
[36] \quad & \sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{c\in C}\sum_{n\in N}\sum_{t\in T}\left(g^{\text{market}}_{rucnt}\sum_{a_c^-}^{a_c^+} D_{raunt}\right) + \sum_{s\in S}\sum_{u\in U}\sum_{t\in T}\left(g^{\text{byproducts}}_{sut}\sum_{r\in R_{(s)}}\sum_{a\in A}\left(\gamma_{rau}M_{raut}\right)\right) \\
& - \sum_{i\in I}\sum_{t\in T}\left(c^{\text{H}}_{it}X_{it}\sum_{r\in R}v_{ri}\right) - \sum_{r\in R}\sum_{i\in I}\sum_{t\in T}v_{ri}f_{rit}X_{it} \\
& - \sum_{u\in U}\sum_{i\in I_{(Ku)}}\sum_{r\in R_{(u)}}\sum_{t\in T}\left(c^{\text{T}}_{riut}\sum_{a\in A}Y_{raiut}\right) \\
& - \sum_{r\in R}\sum_{i\in I}\sum_{t\in T}\left(c^{\text{S}}_{rit}\sum_{a\in A}I^{\text{F}}_{rait}\right) - \sum_{u\in U}\sum_{r\in R_{(u)}}\sum_{t\in T}\left(c^{\text{S}}_{rut}\sum_{a\in A}I^{\text{U}}_{raut}\right)
\end{aligned}
$$

Subject To:

[2]-[8], [10], [11], [13], [15], [17]-[21], [28], [31]

The first and second term of the objective function represents revenues from the sales of end products and chips. The third and fourth terms are the harvesting cost and stumpage fees. The fifth term is the transport cost, while the last two terms are the storing costs at roadside and the log yard.