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A Mixed Integer Programming Model to Evaluate Integrating Strategies in the Forest Value Chain – A Case Study in the Chilean Forest Industry

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Abstract. When a company is integrated vertically, it can manage and plan its overall value chain in one direct approach. However, in many cases, companies follow a decoupled approach where forests and production plants optimize separately their processes in a supply driven strategy. In Chile, the two largest forest companies are vertically integrated (i.e. they own forest and mills that produce logs, lumber, plywood, pulp, paper, and bioenergy, etc.). Historically, they have coordinated their value chains using a make-to-stock strategy, for which the forest is the main driver of the value chain activities. In this paper, we propose an integrated planning approach to show the impacts of a demand driven integration of the value chain in the forest industry. To compare this strategy with the decoupled strategy, we develop a Mixed Integer Programming (MIP) model for the integrated strategy. To illustrate our proposal, we use forest and production information from a Chilean forest company. The decoupled strategy, where the forest and the industry planning are planned separate, uses two models. The first model deals with the forest management and harvesting decisions and maximizes the expected net present value of logs. In this model, the planning period covers one full forest rotation, which in Chile corresponds to about 25 years. The second model maximizes the net present value of the downstream operations for a shorter business planning period (five years) constrained by the availability of the logs from the first model. In the integrated approach, all parts of the value chain (forest, transportation and mills) are driven by final product demand and where the objective is to maximize the profit of the company (net present value of the entire value chain). The demand is given for the shorter business planning period. The two strategies are evaluated using the MIP model, and the net present value (NPV) is used to determine the best practice. According to the results, the NPV can increase with up to 5.0% when the proposed integrated strategy is implemented as compared to a decoupled strategy. Moreover, the profit for the business period increases with up to 8.5%.

Keywords. Value chain management, forest industry, push and pull strategies, long term forest planning, mixed integer programming.

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1 Introduction

The value chain (VC) in the forest industry starts with harvesting operations where different log types (for example saw logs, pulp logs and fuel logs) are produced in the bucking process. The logs are defined through attributes (for example species, grades, dimensions, etc.) and volume proportions are based on tree characteristics (for example age, diameter, length and location). Logs are the raw material for the primary transformation mills, which produce final or intermediate products (for example lumber, plywood, pulp, energy, etc.) for customers and secondary transformation mills. It is important to note that the VC is a divergent chain with one-to-many processes. Hence, the coordination and the planning of the VC can produce many diverse outcomes according to the strategy used for managing it. A recent description of the forest supply chain and planning problems is found in D'Amours et al (2008).

In this paper, we compare two different planning strategies. In the first strategy, the planning of the forest and the industry is decoupled and planned in a sequential approach. The forest is planned first with the objective of maximizing the expected net present value of timber, and the industry is planned second, with the objective of maximizing the actualized profits constrained by the availability of the logs. The first part must satisfy a set of harvest volume restrictions, for example, non-declining yield constraints and limits between consecutive years. The first part covers a planning period of at least one rotation (for example, 25 years) whereas the second cover a shorter period (for example, five years) where the demand and product prices can be estimated. We will use the notation business planning period for the shorter horizon. This approach can be viewed as a decoupled strategy where logs become available for further transformation. It is compared with an integrated strategy were all parts of the value chain (forest and mills) are driven by both a final product demand over the business planning period and an estimation of the forest value over the remaining periods, and where the objective is to maximize the total expected long term profit of the company.

The main difference between the decoupled and integrated approaches is how the VC planner uses the demand information and plans simultaneously the different activities. Under the decoupled strategy, the forest manager plans the harvesting and log transportation activities in order to optimize an expected net present value of the logs. In the integrated strategy, the forest planning over the business planning period is driven by demand of final products and all the value chain activities are synchronized to maximize profit and response to the estimated end product demand (Giunipero et al., 2008). The forest value chain has traditionally been managed under a decoupled strategy as forest companies have not integrated well the forest planning with the industrial logistic and production planning. In the same manner, the logistics and production planners have used the availability of logs as constraint without any possibility to alter. They also do not review their production plans to better align with the expected forest outputs.

The literature shows multiple optimization models developed for forest management planning, with some models supporting decisions such as: which silvicultural regimes to apply in a forest, which stands to harvest per time period, what is the optimal rotation age, etc. Some of these approaches are based on linear or mixed integer programming models. To optimize a forest management strategy, these models explicitly deal with forest growth and management, sustainability issues as well as forest structural constraints (Gunn, 2007). Some of these models also aim to support short term harvesting decisions and timber production decisions (Epstein et al., 2007). If forest and mills decisions are not integrated, it will lead to sub-optimality as mills can not optimize benefits because they need to adapt their production process to the available logs at a specific time, and on the other side, forest owners cannot maximize their returns from the forest as they do not take into account the needs of the market. As the planning process is carried out, present forest managers plan harvest and bucking operations based on internal transfer prices received for each forest product. These internal transfer prices are viewed as coordination mechanisms to help aligning the forest supply and the industry demand. They are part of decoupled planning approaches. In addition there may be contact terms setting minimum supply to mills. This leads to situations where managers at mills receive logs that are not the best fit for the demand they face in terms of specific boards to be produced (Weintraub et al., 2000). The forest literature for long range planning has been focused on managing the forest with little anticipation of downstream industrial activities, only considering basic rules of timber production (non declining yields) or minimum and maximum required timber availability. In some cases, the supply of timber is differentiated into a few categories, like pruned logs, sawlogs, pulp logs, this is however still far from demand requirements in downstream activities which are more detailed in terms of log definitions (lengths, diameters). Well known long range forest models include, Timber Ram (Navon, 1971), Forplan (Kent et al., 1991), Spectrum (Greer and Meneghin, 1999), all developed for the US Forest Service, which takes no consideration of downstream operations. The reason is that the US Forest Service sells the right to harvest on its lands, and thus has no information or interest on detailed further technical use of logs. Later systems are increasingly concerned with the environmental issues in the management of forests. Folpi (García, 1984) was widely used in New Zealand, and its use was focused for the nationally owned forests. Long range models used in Chile and Brasil (Epstein et al., 1999) also do not integrate with downstream industrial facilities. This is also true for the Nordic countries. The Heureka Forestry Decision Support System (DSS) (www.slu.se/heureka) is a suite of freely available softwares developed and hosted by the Swedish University of Agricultural Sciences (SLU) as a free service to society. The system covers the whole decision support process from data inventory to tools for selecting among plan alternatives with multi-criteria decision making techniques. The software covers stand-level analysis as well as forest-level planning and analysis. There is currently no connection to downstream activities with a given demand description. However, there is currently initiatives to integrate the forest planning with road investment (Karlsson et al, 2006) which is connected to downstream activities.

Tactical models with even shorter time horizons have little detailed integration with downstream industrial operations, aggregating logtypes into a few classes and concentrate the analysis in the forest management. For example Andalaft et al. (2003) in Chile, and Church (2007), relate basically to the forest management. We also find forest harvesting models that considers detailed log transference (lengths, diameters) to downstream operations at operational level, with horizons of 10-12 weeks (Weintraub et al., 1999). For longer range planning, it is difficult to find work that integrates the forest modeling with downstream industrial operations. If the mill and forest managers could simultaneously define the stands to be cut, the bucking patterns to be applied in each stand (and therefore, the amount and quality of logs), the transportation volumes and destinations (mills), the mill processes to run, they would be able to manage the whole value chain under the integrated strategy defined in this paper. Moreover, they could maximize the net present value for the whole value chain. The feasibility of coordinating the value chain under an integrated approach depends on the willingness of the planners and managers belonging to the different constituents of the VC to work together (see Figure 1). According to Balakrishnan et al. (2002), Simchi-Levi et al. (2003) and Simchi-Levi et al. (2005), the success of VC is closely linked to how efficient the integration of suppliers, manufacturers, distributors and retailers are.

The main contributions of this paper are the following. First, we propose an integrated planning strategy and a generic MIP model that solves the integrated problem. Second, we make an analysis between the traditional decoupled strategy and show that the integrated strategy is more efficient in terms of the NPV value and even more in terms of profitability during the business period. This paper is organized as follows. First, we describe the two planning strategies in Section 2. After that, we present the mathematical model developed to evaluate the integrated and decoupled strategies in Section 3. In Section 4, we describe the case study based on a Chilean company. The results from the analysis is presented in Section 5. Finally, we make some concluding remarks in Section 6.

2 Problem description

The value chain studied in this article has a structure similar to the two largest Chilean forest holding companies (Arauco and CMPC). The VC used is illustrated in Figure 1 and is composed of three parts. The first part includes the forest units, which are responsible for supplying the logs to the mills, which constitute the second part of the VC. The third part is composed of the secondary mills, the distribution centers, the retailers and the final customers.

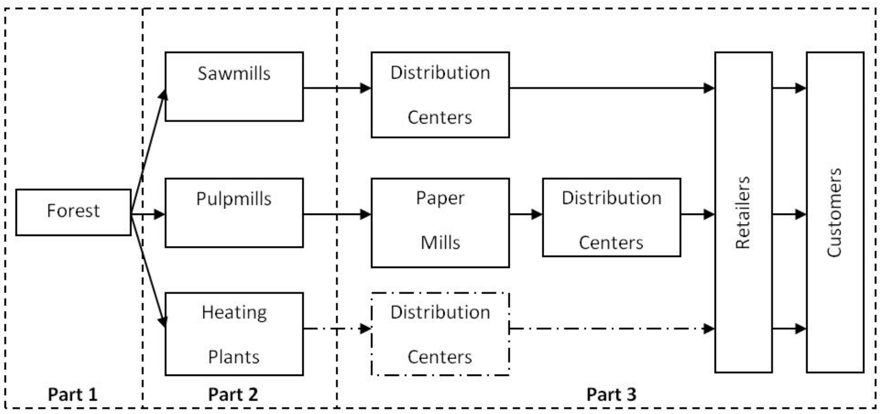

Figure 1: Illustration of the structure of the forest value chain in Chile.

Referring to Figure 1, it is possible to understand how a VC works in the Chilean forest sector. Although the most important forest holdings are integrated vertically in Chile, each business unit, i.e. the forest unit and each one of the mills (at any parts), are managed independently. The coordination is made using internal transfer prices, and thereby, each business focus on optimizing their own objective.

The forest manager wants to maximize the NPV value of the forest. The planning is done over at least one rotation and the objective is to maximize the net present value. The forest is divided into a set of forest areas, each representing the smallest unit to harvest at one time. The decisions included are which harvest areas to harvest and when. Also, there is a decision on which bucking pattern to use for each harvested area at each time period. A bucking pattern is a list of possible products (for example different sawlogs and pulplogs) and the proportion of which they are produced when applied to a harvest area. One bucking pattern may, for example, produce more pruned logs than other bucking patterns. Different patterns focus on different log types. To compute the net present value, we need an estimate of the sales value of each of the log types for the entire planning period. This is difficult and the standard approach is to use current market prices minus some average transportation cost throughout the entire planning period and then use a discount rate to compute the NPV. This is assessed by the forest manager and takes into account the fact that we base the value on the logs by roadside i.e. before any transportation is done. To control the production to specific products that fits the profile of the company´s mills, the company will typical use transfer prices. These are estimated by the forest manager and are aimed to reflect the needs of the mills. In this step, we also take into account constraints on non-declining harvest levels. This long term planning uses time periods of five years. This means that the forest unit will look to increase its income, and thus, the forest manager will decide, for example, to apply bucking patterns that generate a higher volume of logs with better expected prices (e.g. pruned logs), and will only meet the minimal estimated demand for logs with lower expected value (e.g. pulp logs). Under those conditions, mill planners can only adapt their requirements to the logs that the forest unit produces and sells.

The mill manager does not work with a planning period of a full forest rotation. The planning horizon may consider one year with detailed data and some estimates of demand for some additional years. We can view this as a tactical planning, and where we have the available volumes from the long term planning as a basis. In addition, we have a description of the estimated demand for each time period. In this short term planning, we also need to consider transportation and production at the mills. In this model, the decisions are flows between harvest units and mills, between mills, production at mills and flows to final customer demand. In our case, the customer demand is not fixed. Instead, we use a piecewise linear price curve with break points to better describe a real market behavior toward different volume of production. This is illustrated in Figure 2. As the volume increases, the market price will be lower and the overall value will be described by a concave function.

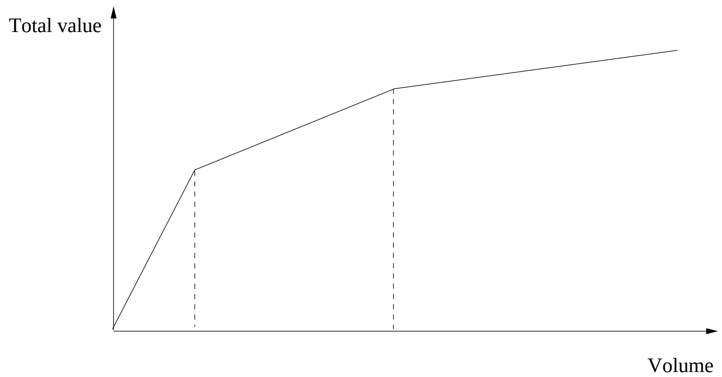

Figure 2: Illustration of the price curves with fixed breakpoints.

In this paper, we compare two different strategies. The first relates to the traditional forest approach and can be viewed as a decoupled, or sequential, approach. There are several reasons why this approach is used in practice. If the company is not vertically integrated, this is a natural approach as there is no connection to other planning units. In our case study, the companies are vertically integrated but due to planning methods and traditions they still use a decoupled approach. In this decoupled strategy, the forest planner determines the optimal harvesting and log production decisions. It maximizes the NPV for the forest unit (NPV-F). Later on, the mills' planners set their production in order to meet demand and maximize the NPV for the mills (NPV-M). An illustration of this approach is shown in Figure 3. It is easy to understand the basic principles. The second approach relates to an integrated strategy where there is a demand given (as in Figure 2) for each final product. In this integrated strategy, the forest planner and the mills planners coordinate the operations of the whole VC. The planners maximizes the total NPV of all business units (NPV-FM). Figure 4 illustrates this situation.

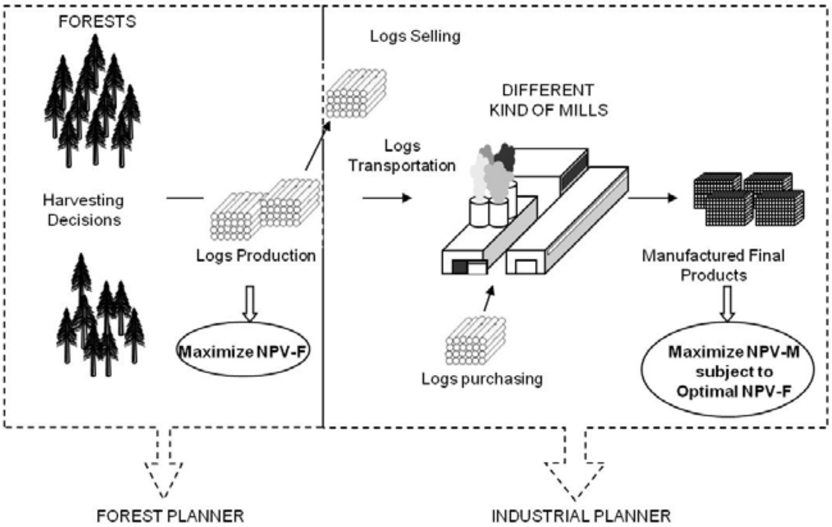

Figure 3: Illustration of the decoupled strategy.

To evaluate the two different strategies, we develop a Mixed Integer Programming (MIP) model. This model describes the integrated planning problem and when we want to study the decoupled approach, we simply solve it in a two phase heuristic corresponding to the two phases. In the first phase, we include the harvest and bucking decisions over the full planning period. We can view this problem as the forest planning model. In the second phase, we use the volumes available for the first five years and solve the remaining downstream part. In practice, we simply fix the decisions made from the forest planning model. We call this second problem the transportation and production planning problem. For the decoupled strategy, the transportation and production planning problem is constrained by the harvesting solutions, obtained by the solution from the forest planning problem, to optimize the industrial plants. As a result, it provides the NPV of the decoupled strategy (this is equivalent to maximizing the NPV-M subject to the NPV-F which is already maximized as shown in Figure 3). For the integrated strategy, the MIP model is used with the original data and provides the NPV for the integrated strategy (or NPV-FM in Figure 4).

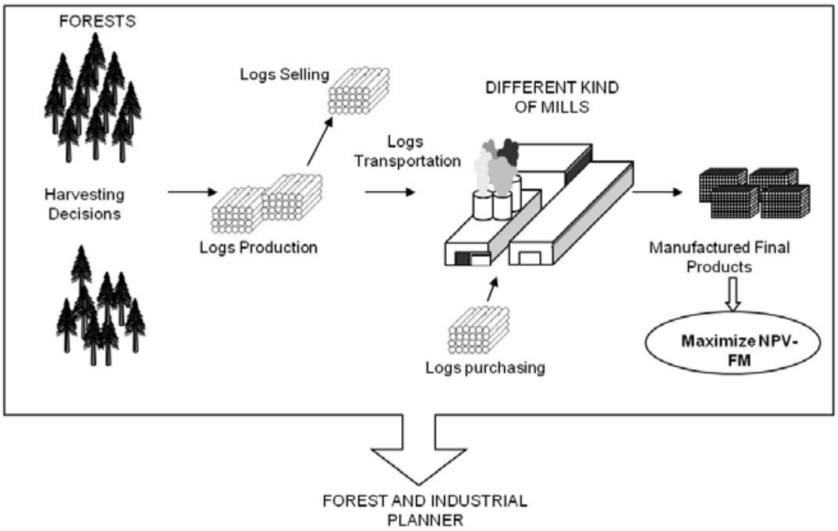

Figure 4: Illustration of the integrated strategy.

3 Planning model

In this section, the mathematical formulation is developed together with a description of the underlying assumptions. The MIP model considers a planning horizon (T) that normally spans over a minimum of one full rotation. The planning horizon is characterized by a business planning horizon (TB) of yearly periods and an anticipation planning horizon (TA) of N-year-periods. Figure 5 provides an illustration where the business period covers five time periods of one year and the anticipation covers 20 years with time periods of five years. The harvest decisions made in the business planing period will be executed whereas the harvest decisions made in the anticipation period is just used for evaluation of the long term forest management solution. Also, the transportation and production decisions are also used to better estimate the value of the harvest decisions.

Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Planning Periods	1	2	3	4	5	6					7					8					9				
	Business Planning Horizon (TB)					Anticipation Planning Horizon (TA)																			

Figure 5: Example of a planning horizon used in the MIP model.

The integrated model maximize the NPV including parts for

- sales value during the business period
- expected value over the anticipation period
- transfer cost during the business period (only used in the decoupled strategy)

- production cost during the business period
- transportation cost of logs/products during the business period
- harvesting cost during both business and anticipation period
- value of standing timber at the end of the planning horizon

This value chain structure includes harvest areas, sawmills, pulp mills, heating plants and customers. There is a number of harvest areas in the forest and each area must be harvested entirely or not in the same time period. The mills are supplied with different kinds of logs (sawlogs, pulp logs and fuel logs) as well as process residues (chips, saw dust and bark) obtained from harvesting and bucking operations. The mills are only assumed to be operated during the business period. The reason is that the demand forecast becomes to uncertain after the business planning period. Logs produced in the anticipation period are valued according to the estimated sales value. Sawmills produce a set of final products which are obtained through cutting processes. A cutting process consumes a specific log type and breaks it down into a set of products, including chips and fuel residues. Pulp mills produce different types of pulp using specific recipes. A recipe consumes a specific log type or chip type and produces a specific pulp product. Heating plants produce energy (MWh) from wood including logs, chips and residues. The customers are represented by the demand curves for the products.

The forest has an initial state where each harvest area has a given age. Based on growth curves, we can model how the volume increases during the planning period. Once a harvest unit is cut, we assume that trees are replanted and we model the growth. There is also a minimum age for harvest area to be cut. Moreover, in order to satisfy forest management rules, we have minimum and maximum allowed harvest levels between planning periods. Some of these constraints enforce the status of the forest at the end of the planning period to be similar to the current status.

Parameters used in the model

The index sets used in the model are as follows.

T_B	:	set of time periods in the business planning ($T_B = \{t_1^B, t_2^B, \ldots, t_{n_B}^B\}$)
T_A	:	set of time periods in the anticipation planning ($T_A = \{t_1^A, t_2^A, \ldots, t_{n_A}^A\}$)
T	:	set of time periods ($T = T_B + T_A$)
I	:	set of harvest areas
I_t^t	:	set of harvest areas that cannot be harvested in time period t
J	:	set of mills ($J^{saw} \cup J^{pulp} \cup J^{heat}$)
K	:	set of tree types
L	:	set of log types
D_p^P	:	set of process materials for process p
D	:	set of products
P^B	:	set of bucking patterns/processes
P_j^J	:	set of processes at mill j
N	:	set of price levels

The parameters used to describe harvest areas, production at mills and allowable harvest levels are given below.

s_{ikt}	:	volume of tree type k in harvest area i in time period t
s_{it}^0	:	total volume at harvest area i in time period t
g_{it}	:	capacity required to harvest area i in time period t
h_t	:	harvest capacity in time period t
a_{ipklt}^B	:	conversion rate of bucking process p from tree type k to log type l at harvest area i in time period t
a_{pld}	:	conversion rate of process p using incoming flows of log type l or product d to produce product d
$\overline{e}_{jt}$	:	upper production capacity in mill j during time period t
$\underline{e}_{jt}$	:	lower production capacity in mill j during time period t
b_{dnt}	:	total demand volume on level n for product type d in time period t
a_t^-	:	maximum allowed decrease in harvesting yield from time period t to the next
a_t^+	:	maximum allowed increase in harvesting yield from time period t to the next
a^{a-}	:	minimum allowed harvesting yield compared to average yield
a^{a+}	:	maximum allowed harvesting yield compared to average yield
V_t^0	:	volume of forest with certain age in the beginning of the planning horizon. The age corresponds to the age the forest will be at the end of the planning period if it is harvested in time period t
v_{it}^n	:	volume of forest at harvest area i at the end of the planning horizon if it is harvested in time period t
v_i^1	:	volume of forest at harvest area i at the end of the planning horizon if not harvested
V^2	:	total volume of forest older than the number of years included in the anticipation period at the beginning of the planning horizon

There are many costs and values used in the model, and these are given below. Each value or cost parameter is computed taking into account a discount rate factor of α according to $1/(1+\alpha)^{t-1}$.

v_{dnt}^d	:	unit market value on level n for product type d in time period t
v_{lt}^h	:	value of log type l in time period t at harvest areas minus an average transportation cost in time period t
v_{it}^e	:	ending value (in last time period) of harvest area i if harvested in time period t
v_i^0	:	value of harvest area i if not harvested
c_{it}^h	:	harvest cost at harvest area i in time period t
c_{jpt}^p	:	unit process cost to run process p at mill j in time period t
c_{ijt}^t	:	unit transportation cost from harvest area i to mill j in period t
c_{ijdt}^d	:	unit transportation cost from mill i to mill j in period t of product d
M	:	penalty cost for not fulfilling the lower production level at mills

The decision variables used in the models are:

$$z_{it} = \begin{cases} 1, & \text{if harvest area } i \text{ is harvested in time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$z_i^0 = \begin{cases} 1, & \text{if harvest area } i \text{ is not harvested} \\ 0, & \text{otherwise} \end{cases}$$

y_{ikpt}^B = volume of tree type k using bucking process p in period t at harvest area i

y_{jpt} = volume of process p used at mill j in period t

x_{ijlt}^l = flow from harvest area i to mill j in period t of log type l

x_{ijdt}^d = flow from mill i to mill j in period t of product d

x_{ilt}^s = logs not transported to mills from harvest area i in period t of log type l

w_{jdt} = production at mill j of product d in time period t

u_{dnt}^d = production of product d at demand level n in time period t

u_{ilt}^h = sold logs of log type l at harvest area i in time period t

s_{jt} = not fulfilled production level at mill j in time period t

Mathematical Model

The MIP model can be expressed as

$$\max \quad z = \sum_{d\in D}\sum_{n\in N}\sum_{t\in T_B} v^d_{dnt}u^d_{dnt} + \sum_{i\in I}\sum_{t\in T} v^e_{it}z_{it} + \sum_{i\in I} v^0_i z^0_i + \sum_{i\in I}\sum_{l\in L}\sum_{t\in T} v^h_{lt}u^h_{ilt} - \sum_{i\in I}\sum_{j\in J}\sum_{l\in L}\sum_{t\in T} c^t_{ijt}x^l_{ijlt} - \sum_{i\in J}\sum_{j\in J}\sum_{d\in D}\sum_{t\in T} c^d_{ijdt}x^d_{ijdt} - \sum_{i\in I}\sum_{t\in T} c^h_{it}z_{it} - \sum_{j\in J}\sum_{p\in P^J_j}\sum_{t\in T_B} c^p_{jpt}y_{jpt} - \sum_{j\in J}\sum_{t\in T_B} Ms_{jt}$$

subject to

$$\sum_{t\in T} z_{it} + z^0_i = 1, \quad i\in I \tag{1}$$

$$\sum_{p\in P^B} y^B_{ikpt} = s_{ikt}z_{it}, \quad i\in I, k\in K, t\in T \tag{2}$$

$$\sum_{k\in K}\sum_{p\in P^B} a^B_{ipklt}y^B_{ikpt} = \sum_{j\in J} x^l_{ijlt} + x^s_{ilt}, \quad i\in I, l\in L, t\in T \tag{3}$$

$$x^s_{ilt} \geq u^h_{ilt}, \quad i\in I, l\in L, t\in T \tag{4}$$

$$\sum_{p\in P^J_j}\sum_{d\in D} a_{pld}y_{jpt} = \sum_{i\in I} x^l_{ijlt}, \quad j\in J, l\in L, t\in T_B \tag{5}$$

$$\sum_{p\in P^J_j}\sum_{l\in D} a_{pdl}y_{jpt} = \sum_{i\in I} x^d_{ijdt}, \quad j\in J, d\in D, t\in T_B \tag{6}$$

$$\sum_{p\in P^J_j}\sum_{l\in D^P_p} a_{pld}y_{jpt} = w_{jdt}, \quad j\in J, d\in D, t\in T_B \tag{7}$$

$$w_{jdt} \geq \sum_{i\in J} x^d_{jidt}, \quad j\in J, d\in D, t\in T_B \tag{8}$$

$$\sum_{n\in N} u_{dnt} = \sum_{j\in J} w_{jdt}, \quad d\in D, t\in T_B \tag{9}$$

$$\sum_{i\in I} g_{it}z_{it} \leq h_t, \quad t\in T \tag{10}$$

$$\sum_{d\in D} w_{jdt} \leq \overline{e}_{jt}, \quad j\in J, t\in T_B \tag{11}$$

$$\sum_{d\in D} w_{jdt} \geq \underline{e}_{jt} - s_{jt}, \quad j\in J, t\in T_B \tag{12}$$

$$u^d_{dnt} \leq b_{dnt}, \quad d\in D, n\in N, t\in T_B \tag{13}$$

$$\sum_{i\in I} s^0_{it}z_{it} \geq a^-_t \sum_{i\in I} s^0_{i,t+1}z_{i,t+1}, t\in T : t\neq t^B_n, t\neq t^A_n \tag{14a}$$

$$\sum_{i\in I} s^0_{it}z_{it} \leq a^+_t \sum_{i\in I} s^0_{i,t+1}z_{i,t+1}, t\in T : t\neq t^B_n, t\neq t^A_n \tag{14b}$$

$$\sum_{i\in I}\sum_{t\in T_B} s^0_{it}z_{it} \geq a^-_{t^B_{n_B}} \sum_{i\in I} s^0_{i,t^A_1}z_{it^A_1}, \tag{15a}$$

$$\sum_{i\in I}\sum_{t\in T_B} s^0_{it}z_{it} \leq a^+_{t^B_{n_B}} \sum_{i\in I} s^0_{i,t^A_1}z_{it^A_1}, \tag{15b}$$

$$\sum_{i\in I} s^0_{it}z_{it} \geq a^{a-} \sum_{i\in I}\sum_{\bar{t}\in T} s^0_{i\bar{t}}z_{i\bar{t}}/(n_A+1), \quad t\in T_A \tag{16a}$$

$$\sum_{i\in I} s^0_{it}z_{it} \leq a^{a+} \sum_{i\in I}\sum_{\bar{t}\in T} s^0_{i\bar{t}}z_{i\bar{t}}/(n_A+1), \quad t\in T_A \tag{16b}$$

$$
\begin{aligned}
\sum_{i\in I}\sum_{t\in T_B} s^0_{it} z_{it} &\geq a^{a-}\sum_{i\in I}\sum_{t\in T} s^0_{it} z_{it}/(n_A+1), && (17a)\\
\sum_{i\in I}\sum_{t\in T_B} s^0_{it} z_{it} &\leq a^{a+}\sum_{i\in I}\sum_{t\in T} s^0_{it} z_{it}/(n_A+1), && (17b)\\
\sum_{t\in T}\sum_{i\in I^t_t} z_{it} &= 0, && (18)\\
\sum_{i\in I} v^n_{it} z_{it} &\geq V^0_t, \quad t\in T_A && (19)\\
\sum_{i\in I}\sum_{t\in T_B} v^n_{it} z_{it} + v^1_i z^0_i &\geq V^2, && (20)\\
\sum_{i\in I}\sum_{t\in T} v^n_{it} z_{it} + v^1_i z^0_i &\geq \sum_{t\in T} V^0_t, && (21)\\
z_{it}, z^0_i &\in \{0,1\}, \quad i\in I, t\in T && (22)\\
\text{all variables} &\geq 0, && (23)
\end{aligned}
$$

The NPV is the sum of the following components:

(1)	$\sum_{d\in D}\sum_{n\in N}\sum_{t\in T_B} v^d_{dnt} u^d_{dnt}$	sales value of products
(2)	$\sum_{i\in I}\sum_{t\in T} v^e_{it} z_{it}$	ending value of harvest area
(3)	$\sum_{i\in I} v^0_i z^0_i$	value from harvest areas not harvested
(4)	$\sum_{i\in I}\sum_{l\in L}\sum_{t\in T} v^h_{lt} u^h_{ilt}$	sale value of logs at harvest areas
(5)	$-\sum_{i\in I}\sum_{j\in J}\sum_{l\in L}\sum_{t\in T} c^t_{ijt} x_{ijlt}$	transportation cost of logs
(6)	$-\sum_{i\in J}\sum_{j\in J}\sum_{d\in D}\sum_{t\in T} c^d_{ijdt} x^d_{ijdt}$	transportation cost between mills
(7)	$-\sum_{i\in I}\sum_{t\in T} c^h_{it} z_{it}$	harvesting cost
(8)	$-\sum_{j\in J}\sum_{p\in P^J_j}\sum_{t\in T_B} c^p_{jpt} y^m_{jpt}$	production cost
(9)	$-\sum_{j\in J}\sum_{t\in T_B} M s_{jt}$	penalty if lower production level at mills is not fulfilled

The constraints are described in text as follows.

(1)	Each harvest area can be harvested at most once
(2)	All volume available must be bucked
(3)	Balance in bucking production and transportation
(4)	Only logs not transported to mills can be sold directly from harvest areas
(5)	Balance in transportation and inflow to mills
(6)	Balance in transportation between mills (by products)
(7)	Balance of products at mills
(8)	Balance of by products at mills
(9)	Balance in demand levels and production
(10)	Harvest capacity
(11)	Maximum production levels
(12)	Minimum production levels
(13)	Correct level of demand levels
(14a-b)	Non-declining yield/harvesting
(15a-b)	Non-declining yield/harvesting between business/anticipation period
(16a-b)	Limits of harvesting in anticipation periods based on average harvest levels
(17a-b)	Limits of harvesting in all business periods together based on average harvest levels
(18)	The forest has to be a certain age before harvest
(19)-(20)	Volume requirement of forest of certain age at the end of the planning horizon
(21)	Requirement of total volume of forest at the end of the planning horizon
(22)	Binary restriction
(23)	Non-negativity restrictions on variables

Constraint sets (19) – (21) need to be explained in more detail. Constraint set (19) forces the forest to regain its structure at the end of the planning period. For each time period, it forces the harvesting and tree planting activities to be driven such that every age class is expected to be restored to at least its initial volume. Constraint set (20) makes sure that the business planning do not over-cut the forest for short term return. The constraints evaluate the volume of planted trees before the end of the business horizon and sum this volume to the volume of trees not harvested during the total forest planning period. This sum should be at least the initial volume of trees of age equal to the years within the anticipation period. Finally, constraint set (21), forces the total volume available at the end of the planning exercise to be at least the initial volume.

We have tested three different approaches to the planning process, one integrated and two sequential. We have used two sequential approaches to better mimic different behaviour in the planning process. Each of the sequential approaches first maximizes the NPV using commercial prices. As a result, we get which harvest areas should be harvested for each time period. In the next step, we determine which bucking patterns to use for the first five years using transfer prices. In the third step, we use the available logs and optimize the transportation and production. The difference between the two sequential versions is that the first sequential approach uses one aggregated 5-year time periods instead of five 1-year periods for the first five years. The areas to be harvested in the first five years then becomes a constraint to the tactical planning, where for each year, harvest areas and bucking patterns are decided. The bucking is then optimize on the volume to be harvested over the first five years using transfer prices. The two versions together with the integrated version can be summarized as follows.

Integrated version (Int):

Step 1 Solve integrated tactical/strategic forest/production/sales planning with both 1 and 5 year intervals using demand levels and prices. As a result, we get the full solution. This solution is found by solving the entire MIP model.

Sequential version 1 (S1):

Step 1 Solve strategic forest planning with 5 year intervals using (estimated) commercial prices. As part of the solution, we have which stands to harvest the first five years but not the exact harvest year. Here, we solve a reduced model with the variables $z_{it}, z_i^0, y_{ikpt}^B$ and u_{ilt}^h where we have aggregated all periods T_B into one period. Values in the objective function as well as volume estimates for the first 5 year interval are taken from year 3. The NPV components (1), (2), (3), (4) and (7) comprise the objective. The variables z_{it} and y_{ikpt}^B for the time periods T_A and the variables z_i^0 are then fixed in the next steps.

Step 2 Solve tactical forest planning with annual time periods and with internal transfer prices. As part of the solution we have which stands to harvest each year together with which bucking pattern to use for each stand. We disaggregate T_B and solve a reduced model with the variables z_{it} and y_{ikpt}^B. This problem is only solved for the business periods T_B. The harvest areas to be harvested are limited to the once that were harvested in the aggregated periods t_B in Step 1. Transfer prices are used to evaluate the log types produced instead of commercial prices. Hence, the objective comprise of the transfer prices and the NPV components (3) and (7). The transfer prices are expressed as $+\sum_{l\in L}\sum_{t\in T} q_{lt}^t (\sum_{i\in I}\sum_{k\in K}\sum_{p\in P^B} a_{ipklt}^B y_{ikpt}^B)$ where q_{lt}^t = transfer price of log type l in time period t. The variables z_{it} and y_{ikpt}^B for the time periods T_B are then fixed for the next step.

Step 3 Solve tactical production and sales problem given available volumes at stands each year and the demand levels and prices. The variables are $y_{jpt}^m, x_{ijlt}^l, x_{ijdt}^d, x_{ilt}^s, w_{jdt}^m, u_{dnt}^d, u_{ilt}^h$ and s_{jt}. The NPV is used as objective.

Sequential version 2 (S2):

Step 1 Solve strategic forest planning with both 1 and 5 year intervals using (estimated) commercial prices. As part of the solution we have which stands to harvest each of the first five years (i.e. a more detailed plan as compared to version 1). The solve a reduced model with the variables $z_{it}, z_i^0, y_{ikpt}^B$ and u_{ilt}^h. The NPV components (1), (2), (3, (4) and (7) comprise the objective. The variables z_{it} (for all time periods) and y_{ikpt}^B (for the time periods T_A) and the variables z_i^0 are then fixed in the next steps.

Step 2 Solve tactical forest planning with annual time periods and with internal transfer prices. As a solution we have which bucking pattern to use for each stand (the time period to harvest was decided in step 1). We solve a reduced model with the variables y_{ikpt}^B. This problem is only solved for the business periods T_B. The objective comprise of the transfer prices and the NPV components (3) and (7). The variables y_{ikpt}^B for the time periods T_B are then fixed for the next step.

Step 3 Solve tactical production and sales problem given available volumes at stands each year and the demand levels and prices. The variables are $y_{jpt}^m, x_{ijlt}^l, x_{ijdt}^d, x_{ilt}^s, w_{jdt}^m, u_{dnt}^d, u_{ilt}^h$ and s_{jt}. The NPV is used as objective.

4 Description of Chilean Case Study

In this section, we outline the design of the case study based on a Chilean company. The firm we consider owns forest lands, composed of multiple stands, or cutting blocks which each is supposed to be harvested in a single period or not at all. The firm has 17 separate forests, which were jointly considered in Andalaft et al (2003). For our case, we consider only one forest, the largest one, to make our analysis. Figure 6 illustrates the geographical setup of the problem. The forest is composed of different spatially located stands or harvest areas, with one species planted, radiata pine, but with differences in stands related to age, diameter, quality (defects) and density. This makes logs from different harvest areas better suited for different mills, destinations and types of products. The logs obtained from these areas are used to supply plants downstream. These plants correspond to three saw mills, one pulp mill and one heating plants. Logs of different characteristics are transported from the forest to plants, carrying harvesting and transportation costs. At sawmills there exist several possible sawing patterns which describe how the logs can be cut to generate final products, for example boards of different dimensions. The sawing patterns descriptions are based on statistical analysis of past processes. We have access to this information for all pairs of sawing pattern and log type. At the pulp plant there are recipes which tie the input of logs with final production of pulp. For the heating plant we also have a relationship between logs that are used, as well as bark or chips and the energy produced. All plants have upper processing capacities and processing costs. The saw mills and the pulp plant also have minimum capacities, or minimum amount of volume processed, restrictions. All these final products are sold into the market, facing downward slope price functions, which can be approximated by piece wise linear segments, with decreasing returns. The timber produced in the forest is well matched with the the plants, which have enough capacity to handle all the forest timber production, so that shortfalls to satisfy demand can be avoided. Excess production of logs can be sold in the market. The purpose of developing this case study is to highlight the differences between two approaches and the potential of using an integrated strategy. Our assumption is that the integrated approach can establish better solutions in two ways. First, there is a better match between the produced logs and products at the mills. Second, the production of logs and final products is better coordinated with respect to the market demands.

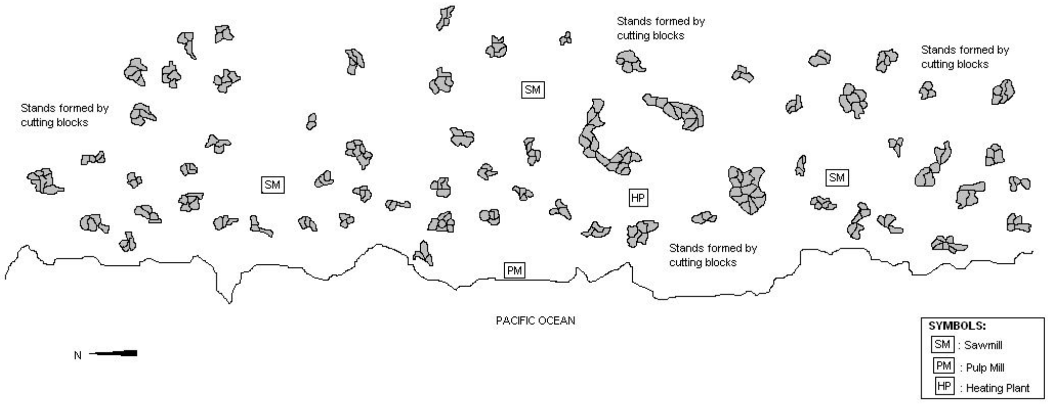

Figure 6: Illustration of the spatial structure of the forest and mills. Only a small part of the harvest areas are given.

In Table 1, we provide some key business information for the company based on the annual reports. We can use this information to compute the studied forest's share of the overall fixed cost and to be able to compare income and profit with the result of the case study.

	2008			2009		
Item	Harvest	Pulp	Sawn wood	Harvest	Pulp	Sawn wood
Pine	5.7	0.760	1.4	5.2	0.760	1.3
Eucalyptus	3.3	1.15		3.2	1.15	
Sales		1029	417		805	346
Operating costs		-591	-251		-506	-245
Other Operating expenses		-58	-15		-23	-9
Depreciation and Stumpage		-89	-29		-173	-72
others		-10	-9		-15	-7
Operating Income		281	113		88	13
Financial Cost		-71	-42		-36	-35
Net Income		210	71		52	-22

Table 1: Business information for the company during 2008 and 2009. All financial values are expressed in million US$, harvest volumes in million m^3 and production in million metric tons.

The total planning period is 25 years. The first five years is the business planning period where we make use of annual time periods. For each year, we have an estimated final demand of the products. The next twenty years are used only for harvest decisions as in a traditional forest management planning. Here we use four five-year periods. We have considered the business horizon at 5 years to be sufficiently long, as it is difficult to forecast exact demand beyond that time into the future, and because analyzing in detail beyond 5 years would not lead to improved analysis. The decisions implemented from the business period are the harvesting decisions. The transportation and production decisions for the mills are also anticipation decisions in that they will not be implemented directly. These decisions will be taken as the demand is confirmed through orders or agreements. This is done on a rolling horizon planning approach. The Chilean company is planning its value chain using a decoupled approach where the forest manager manages the forests for maximum net income or timber production, subject to sustainable production, defined as non declining yield between periods. The forest decisions are: for each period which cutting blocks to harvest, how much timber to harvest from each block and supply downstream, defined by log types. The mills downstream receive as input the logs generated from the forests, and the demand functions from the market. Management allocates the supply in order to maximize profit at the mills. The plant decisions are: which production processes or cutting patterns to run at each mill, and how to transport logs from harvest areas to mills. In discussions with the firm, we have obtained information on the current status of all harvest areas, growth curve for the trees, historical output data on bucking patterns, sawing patterns and production recipes, production capacities, estimated demand and transfer prices used in their own planning.

Table 2 presents the general characteristics of the industrial case.

Harvest areas	{1...1226}
Bucking patterns	{1...7}
Logs types	{Pruned log, Sawlog type1, Sawlog type2 Sawlog type3, Sawlog long, Pulp log and Fuel log }
Sawmills	{1...3}
Sawing patterns	{1...7}
Pulp mills	{1...1}
Heating plants	{1...1}
Final products*	{Lateral Board, Square Board, Long Board, Pulp and Energy}
Demand levels for final products	{1...3}
Planning periods	{1...9}

Table 2: Characteristics of the case study. (* The lateral board is also called side lumber and the square board is known as central piece.)

The volume of the forest with certain age was determined using a growth function provided by Vargas and Sandoval (1998). The volume (m^3/ha) is given by the function $-4.97053x + 2.188126x^2 - 0.04491x^3$, where x is the age of the harvest area. The growth curve is illustrated in Figure 7. The growth curve used in the case study includes a random component. The growth curve in Figure 7 is the average curve but each year has an extra volume based on a random number which is rectangular distributed within the interval [-7.5,7.5]). If the volume from one year to the next decreases for a forest younger than 20 years, it is set to 0. For a forest older than 35 years, the change in volume is also set to 0.

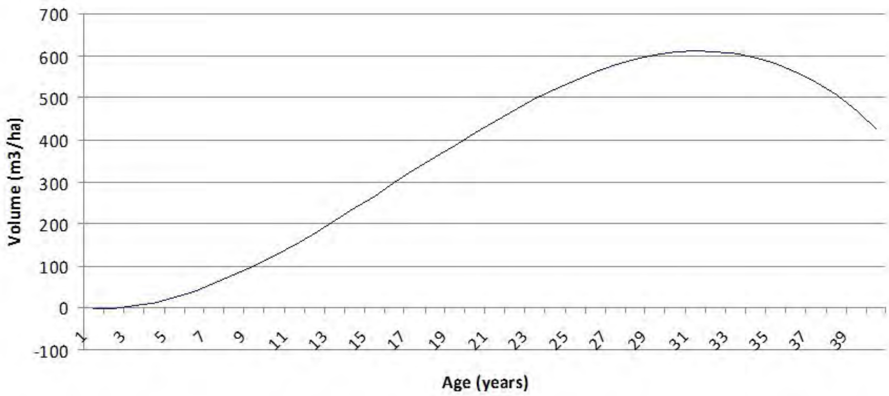

Figure 7: Growth function used for determining the volume of forest.

The economic parameters such as log prices, harvesting and transportation costs, manufacturing costs and a discount rate (8%) were needed. The used values of these parameters are shown in Tables 3 and 4. All this information was prepared by the Chilean firm hosting the case study.

Log Types	Transfer Price (US$/$m^3$)	Commercial Price (US$/$m^3$)
Pruned Logs	48	90
Sawlog Type1	30	54
Sawlog Type2	25	49
Sawlog Type3	21	45
Sawlogs Long	21	45
Pulplog	1	25
Fuel logs	0.1	12

Table 3: Log Prices used in the case study.

Cost	Value (US$/unit)
Harvesting (m^3)	6.5
Transportation forest - mills (per m^3 and km)	0.11
Transportation mills - mills (per ton and km)	0.09

Table 4: Forest operation costs used in the case study.

Conversion factors were also used for the bucking and manufacturing process. For the bucking process, seven bucking patterns define the transformation possibilities when bucking a tree into different kinds of logs. Each bucking pattern establishes percentages for each type of logs that is obtained from it when that pattern is applied to the harvested trees in a given harvest area. The proportion depends on the age of the tree, and hence we have different values for each of the ages 15-50 years. The proportion are presented in Table 5 and they represent only the age 30.

	Log types						
Bucking Pattern	Pruned Logs	Sawlog Type1	Sawlog Type2	Sawlog Type3	Sawlog Long	Pulp logs	Fuel Logs
1	0.12	0.14	0.22	0.18	0.04	0.28	0.02
2	0.05	0.20	0.23	0.16	0.06	0.27	0.03
3	0.15	0.16	0.23	0.16	0.00	0.28	0.02
4	0.00	0.22	0.30	0.09	0.06	0.29	0.04
5	0.08	0.16	0.17	0.18	0.03	0.33	0.05
6	0.00	0.09	0.24	0.09	0.14	0.36	0.08
7	0.12	0.05	0.14	0.07	0.12	0.42	0.08

Table 5: Information about the seven bucking patterns used with a tree age of 30 years. (The figures represent the proportion of the tree (per m^3) for each type of log.)

In Figure 8, we illustrate how the proportion of different log types changes between 15-50 years of age for bucking pattern 1.

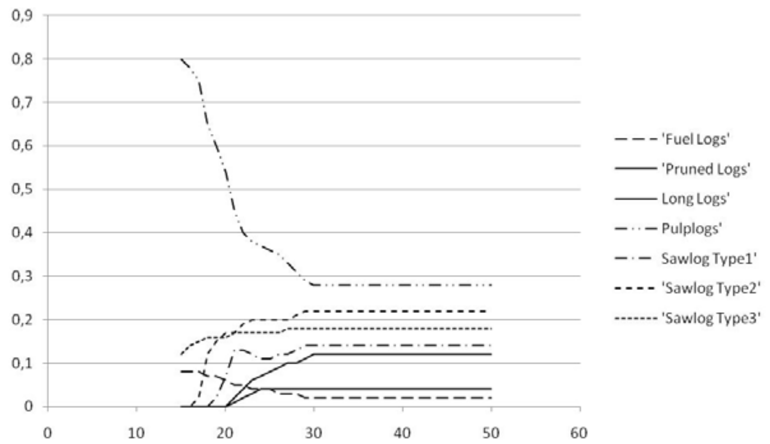

Figure 8: Illustration how the proportion of different logs changes with age for bucking pattern 1.

At the sawmills, we use seven sawing patterns which have different yields according to the used log type. Pulplog and Sawdust can be used for pulp production where one cubic meter yields 0.33 metric tons of Kraft cellulose. In the case of the heating plants, one cubic meter of biomass yields 0.33 MWh. Table 6 shows the proportions of each product and co-product obtained when applying the different processes at the mills.

Sawmill	Sawing pattern	Log type	Product Type	Proportion
Sawmill1	Saw1	Pruned Logs	Lateral Board	0.28832
Sawmill1	Saw1	Pruned Logs	Square Board	0.26208
Sawmill1	Saw1	Pruned Logs	Chips	0.14382
Sawmill1	Saw1	Pruned Logs	Sawdust	0.15578
Sawmill1	Saw1	Pruned Logs	Bark	0.15
Sawmill1	Saw1	Sawlog Type1	Lateral Board	0.26163
Sawmill1	Saw1	Sawlog Type1	Square Board	0.25502
Sawmill1	Saw1	Sawlog Type1	Chips	0.150822
Sawmill1	Saw1	Sawlog Type1	Sawdust	0.187528
Sawmill1	Saw1	Sawlog Type1	Bark	0.145
Sawmill1	Saw6	Pruned Logs	Pruned Board	0.45
Sawmill1	Saw6	Pruned Logs	Sawdust	0.25
Sawmill1	Saw6	Pruned Logs	Chips	0.15
Sawmill1	Saw6	Pruned Logs	Bark	0.15
Sawmill2	Saw1	Sawlog Type2	Lateral Board	0.22704
Sawmill2	Saw1	Sawlog Type2	Square Board	0.24566
Sawmill2	Saw1	Sawlog Type2	Chips	0.160992
Sawmill2	Saw1	Sawlog Type2	Sawdust	0.226308
Sawmill2	Saw1	Sawlog Type2	Bark	0.14
Sawmill2	Saw5	Sawlog Type1	Lateral Board	0.23085
Sawmill2	Saw5	Sawlog Type1	Square Board	0.25675
Sawmill2	Saw5	Sawlog Type1	Chips	0.1539
Sawmill2	Saw5	Sawlog Type1	Sawdust	0.2135
Sawmill2	Saw5	Sawlog Type1	Bark	0.145
Sawmill2	Saw6	Pruned Logs	Pruned Board	0.45
Sawmill2	Saw6	Pruned Logs	Chips	0.15
Sawmill2	Saw6	Pruned Logs	Sawdust	0.25
Sawmill2	Saw6	Pruned Logs	Bark	0.15
Sawmill2	Saw7	Long Logs	long Board	0.45
Sawmill2	Saw7	Long Logs	Chips	0.15
Sawmill2	Saw7	Long Logs	Sawdust	0.25
Sawmill2	Saw7	Long Logs	Bark	0.15
Sawmill3	Saw5	Sawlog Type2	Lateral Board	0.194016
Sawmill3	Saw5	Sawlog Type2	Square Board	0.282584
Sawmill3	Saw5	Sawlog Type2	Chips	0.160992
Sawmill3	Saw5	Sawlog Type2	Sawdust	0.222408
Sawmill3	Saw5	Sawlog Type2	Bark	0.14
Sawmill3	Saw5	Sawlog Type3	Lateral Board	0.179055
Sawmill3	Saw5	Sawlog Type3	Square Board	0.261745
Sawmill3	Saw5	Sawlog Type3	Chips	0.168156
Sawmill3	Saw5	Sawlog Type3	Sawdust	0.256044
Sawmill3	Saw5	Sawlog Type3	Bark	0.135
Sawmill3	Saw7	Long Logs	Long Board	0.45
Sawmill3	Saw7	Long Logs	Chips	0.15
Sawmill3	Saw7	Long Logs	Sawdust	0.25
Sawmill3	Saw7	Long Logs	Bark	0.15
Pulpmill1	Pulp1	Pulplog	Pulp	0.33
Pulpmill1	Pulp1	Pulplog	Bark	0.13
Pulpmill1	Pulp1	Fuel Logs	Bark	0
Pulpmill1	Pulp1	Fuel Logs	Pulp	0
Pulpmill1	Pulp1	Chips	Pulp	0.33
Pulpmill1	Pulp1	Sawdust	Pulp	0.33
Pulpmill1	Sale1	Pruned Logs	Pruned Logs	1
Heating1	Heat1	Fuel Logs	Electricity	0.33
Heating1	Heat1	Sawdust	Electricity	0.33
Heating1	Heat1	Bark	Electricity	0.33
Heating1	Heat1	Chips	Electricity	0.33

Table 6: Yields of the different processes at the mills. The figures represent the proportions obtained from one cubic meter of logs.

5 Results

The optimization model is implemented in the modeling language AMPL and CPLEX 11 is used to solve the model. All experiments are done with a PC i7, 2.67 GHz CPU with 6 GB of memory. We have generated one base case and four groups of instances to test different properties and their impact on the solution. The four groups are classified into discount rate, demand & product value, pulp price and forest growth. This is summarized in Table 7. In total we have 42 instances. After pre-solving, the integrated MIP model consists of about 8,000 binary variables, 20,000 continuous variables and 10,000 constraints. It takes about an hour to solve the problem to an accuracy where the objective is less than 0.05 % from the optimal objective function value.

Instance	Description
A1	base case (with discount rate 8% and pulp price 700)
B2-B15	different interest rates (1-7%, 9-15%)
C16-C24	different demand and product values
D25-D33	different pulp price (300, 350, ... , 650, 750 $/ton)
E34-E42	different realized growth in the harvest areas

Table 7: Information about instances used in the experiments.

We start to analyze the base case denoted A1. The objective function is composed of different cost and benefit components. These contributions are presented in Table 8. It is worth to note that the overall profit during the entire planning period is improved about 17 million $ compared to the two sequential approaches which are very similar. This variation is generated by an increment in mill's production that is easily checked when mill costs and product sale are compared. Moreover, this is achieved with less harvested volume, 18.74 against 19.05 million (m^3). The main difference is that more products (with good value) are produced during the business planning period and at the same time less logs are sold on the market.

Instance A1	Integrated (Int)	Sequential 1 (S1)	Sequential 2 (S2)
Profit	492.11	475.40	475.65
Product Sale	647.44	605.96	607.03
Log Sale	139.26	147.36	147.45
Ending Forest Value	22.43	21.58	21.61
Harvest Costs	-60.72	-60.45	-60.52
Transport Costs	-36.24	-35.35	-35.57
Mill Costs	-220.06	-203.7	-204.35
Starting Forest Volume (million m^3)	8.40	8.40	8.40
Ending Forest Volume (million m^3)	8.65	8.39	8.40
Harvested Volume (million m^3)	18.74	19.05	19.05

Table 8: Economic NPV of components in the objective function (millions of US$) for instance A1 (base case).

In Table 9, we provide information on profit difference, in each time period, between the integrated and the two sequential approaches (S1 and S2). Column "S1" (under "Total NPV") gives the overall improvement in percentage using the integrated approach as compared to the first sequential strategy. The integrated strategy provides much more profit in the first two periods, i.e. periods 1 – 2, compared to the first sequential approach. The profit is more similar in periods 3 – 5 between the integrated and the sequential approaches. One main reason is that the integrated much better establish which products that are most profitable. Also, it is better to decide in which period to harvest areas, how to use cutting patterns for the logs and hence produce certain products depending on the final product value. The volumes available in the different strategies are very similar due to the harvest balance constraints. The difference with the S2 is also large but less than with S1. The main difference between S1 and S2 is that S1 puts more emphasis on harvesting later in the first five years. The reason is that more information is based on the transfer prices as S1 can shift the harvesting year in step 2. The overall improvement of the integrated strategy is in the range 1.53-5.25% compared to S1 and 1.75-5.21% compared to S2. If we compare the profit increase during the business period we have 4.65-8.65% (S1) and 5.02-8.62% (S2), respectively, which confirms that the integrated strategy has a robust performance with changes in demand and products values. We have also tested a version of S2 where we allow a change of harvesting year also in step 2. However, the difference is very small.

	Total NPV		Per 1		Per 2		Per 3		Per 4		Per 5		Per 1-5	
Case	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
A1	3.51	3.46	17.35	11.04	8.86	5.42	2.69	5.65	1.11	5.21	0.06	6.58	6.10	6.52
C16	5.25	5.21	20.91	14.20	11.53	7.64	4.96	8.13	1.74	6.15	1.30	5.37	8.65	8.62
C17	1.53	1.75	10.57	6.26	4.06	1.50	0.36	2.51	3.09	7.44	4.61	8.51	4.65	5.02
C18	3.06	3.00	15.79	9.76	8.37	5.07	2.08	4.96	0.84	4.72	0.15	4.01	5.99	5.93
C19	3.39	3.35	16.45	10.48	8.54	5.26	2.59	5.41	0.93	4.82	0.08	3.90	6.26	6.23
C20	3.55	3.47	17.25	10.89	8.88	5.48	2.76	5.73	1.00	5.00	0.61	4.47	6.66	6.56
C21	3.22	3.20	15.55	10.01	7.96	4.89	2.95	5.64	1.34	5.06	0.99	4.60	6.26	6.24
C22	3.29	3.24	16.72	10.52	8.95	5.52	2.63	5.61	1.16	5.20	0.04	3.96	6.47	6.42
C23	3.52	3.46	17.36	11.05	8.91	5.47	2.74	5.70	0.98	5.07	0.01	3.90	6.57	6.51
C24	3.50	3.47	17.42	11.04	8.86	5.29	2.68	5.72	0.64	4.92	0.21	4.24	6.52	6.50

Table 9: Total NPV and profit improvement in each of the first five planning periods when comparing the integrated approach with each of the sequential.

To study the impact of different growth scenarios, we study Table 10. Here, we have the overall profit for the three planning strategies for ten randomly generated realizations of volume growth. It is clear that the differences are very stable and similar and we can conclude that the difference is not based on particular and different growths, but it is strongly based on the efficiency of the bucking and logs sharing decisions.

In Table 11 we give the overall profit for the three planning strategies and the difference between the integrated and the two sequential approaches for different discount rates. The results shown clearly that the overall profit depends highly on the discount rate in the NPV computations and this is not any surprise. The overall profit improvement is quite similar although it goes down slightly with increased discount rate. The improvement for periods 1 – 5 changes more. One main reason for this is the affect of volume growth compared to discount rate. When the discount rate is higher than the volume growth, the tendency in in the sequential planning strategies to harvest as much as possible in the first periods. A similar behavior is observed with the integrated strategy but to lesser extend as the demand knowledge set different trade-offs in the business planning period. Fixing a proper discount

	Planning strategy			Periods 1–9		Periods 1–5	
Instance	Int	S1	S2	Int-S1	Int-S2	Int-S1	Int-S2
A1	492.1	475.4	475.7	3.51	3.46	6.58	6.52
E34	492.7	477.1	477.2	3.27	3.26	6.07	6.03
E35	493.5	478.3	478.5	3.18	3.14	5.83	5.83
E36	492.0	476.1	476.8	3.33	3.18	6.20	6.01
E37	491.4	475.8	476.3	3.28	3.17	6.24	6.11
E38	491.7	476.0	476.2	3.29	3.26	6.19	6.21
E39	491.6	475.0	475.8	3.48	3.33	6.53	6.32
E40	491.7	475.9	476.2	3.33	3.27	6.26	6.20
E41	493.4	477.9	477.9	3.23	3.24	5.99	6.07
E42	491.1	475.0	475.4	3.39	3.31	6.39	6.29

Table 10: Total profit for the three planning strategies and improvements when the integrated strategy is compared to the two sequential strategies for ten randomly generated growth realizations.

rate in the context of value chain optimization is a challenging task as the practices in forestry and industry are very different. Forestry approaches view the forest as a continuous source of revenue over time and therefore uses discount rates that maintain a stable rent from the forest. Whereas, industry aims for shorter term returns and include in their discount rates risk factors that may shorten the life of the company. Moreover, it considers that it has alternative ways to generate profits and therefore consider this when fixing the expecting return. The discount rates use in industry are normally higher and for mature companies can be of 10-15% while the discount rates use in forestry are typically lower. They vary depending on the growth rate of the forest. In our case, a clear drop in NPV can be observed between rate 5 and 6%. This seems to be in line with the growth rate of the forest. So, when the discount rate is lower than the forest growth the integrated approach performs particularly good as it can take advantage of the demand information and better fit the usage of the forest. While when the discount rate is higher is in the range of 6% to 15% the improvement is still important but decreases with discount rate increase. We should also note that it is not only the growth and discount rate that should be compared. We also need to consider the change of the proportions of products that are produced by different bucking patterns as this give different values. The main change is that the value peak is moved a few years as compared with the volume peak.

The pulp price is also an important factor influencing the overall profit. From, comparing the company's 2008 results with the 2009 results (lower international pulp price due to the financial crisis), one can understand the impact of the pulp price on the financial figures. Table 12 gives the overall profit for different pulp prices. The profit difference between integrated and the two sequential strategies for the first five years grows with the increase of pulp price. These results and theirs performances show the importance of pulp production in the forest VC at Chilean forest sector and demonstrate that pulp mills (and paper mills also) drive the forest business. Again, one can conclude that the capacity to integrate the demand information helps manager better align the production of the forest with the industry needs and therefore provide greater benefit.

Case	discount rate (%)	Total Profit Int	S1	Seq2	Total improvement % Int-S1	% Int-S2	Improvement periods 1-5 % Int-S1	% Int-S2
B2	1	803.7	773.6	773.5	3.89	3.90	9.88	9.96
B3	2	733.5	707.2	706.5	3.73	3.83	9.43	9.67
B4	3	675.2	650.4	649.6	3.82	3.95	9.38	9.65
B5	4	626.3	601.5	600.9	4.12	4.22	9.38	9.58
B6	5	584.8	559.7	560.3	4.49	4.36	9.51	9.30
B7	6	549.3	532.0	533.0	3.26	3.06	6.79	6.48
B8	7	518.7	501.8	502.2	3.37	3.29	6.63	6.54
A1	8	492.1	475.4	475.7	3.51	3.46	6.10	6.52
B9	9	468.8	452.5	452.7	3.60	3.56	6.43	6.38
B10	10	448.3	432.0	432.0	3.77	3.78	6.44	6.45
B11	11	430.0	414.7	415.1	3.69	3.58	6.02	5.86
B12	12	413.6	400.5	401.2	3.26	3.11	5.15	4.93
B13	13	398.8	387.8	388.0	2.86	2.80	4.36	4.28
B14	14	385.4	376.4	377.0	2.40	2.25	3.56	3.31
B15	15	373.3	365.7	366.0	2.08	1.98	3.01	2.86

Table 11: Results with different interest rates.

Case	Total Profit Int	S1	S2	Total improvement % Int-S1	% Int-S2	Improvement per 1-5 % Int-S1	% Int-S2	Pulp price ($/ton)
D25	254.8	252.4	252.3	0.94	0.99	5.85	6.01	300
D26	260.5	257.9	257.7	1.02	1.08	5.96	6.13	350
D27	278.3	275.0	274.8	1.18	1.26	5.96	6.15	400
D28	308.0	303.7	303.5	1.40	1.47	5.57	5.74	450
D29	340.2	334.1	334.0	1.82	1.86	6.04	6.15	500
D30	372.5	364.6	364.5	2.17	2.19	6.02	6.07	550
D31	405.2	395.0	395.0	2.58	2.57	6.19	6.20	600
D32	437.8	425.4	425.6	2.91	2.88	6.24	6.23	650
A1	492.1	475.4	475.7	3.51	3.46	6.58	6.52	700
D33	503.4	486.4	486.7	3.50	3.44	6.47	6.41	750

Table 12: Results with different pulp price.

6 Concluding remarks

We have presented two planning strategies for combining the forest management and the industry planning. The first is a decoupled or sequenced strategy, where the long term forest planning is done first. Here, we have tested two versions depending on the information available when areas to be harvested are planned. Given the availability of logs, we then solve the production and transportation problem over a shorter time horizon. In the sequenced approach, internal transfer prices are used to align the production of timber with the industry needs. This works as the only coordination mechanism. The second approach is to solve an integrated problem where both forest management and production/logistic planning is done simultaneous. We have proposed a MIP model for the integrated version which includes a number of constraints sets protecting the forest structure over time. This model can also be used to simulate the two tested the decoupled strategies by solving different parts of the model in sequence.

The case study is based on aggregated data from an integrated Chilean forest company. The results on a set of instances shows that the integrated strategy produce a NPV value which is 1.53-5.21% higher than the decoupled strategy in ten generated instances. The profit improvement for the first five years is even more. In our case the average profit improvement is 4.65-8.65% for the ten instances. The important result here is that these improvements can be obtained without pressuring the forest. In this case study, we observe a decrease of harvested volume in the integrated approach as compared to the traditionally used decoupled approach. For a company, this has a large positive impact on the shareholder value and cash flow. Also, we do not include any fixed costs in our profit calculations during the business period. If this is done, the improvements by the integrated would be even larger when expressed in percentage as the overall profit (but not difference) would be lower.

When the discount rate used in the NPV calculations increases, the decoupled strategy, focus on harvesting as soon as possible. This can also be described as a very strong focus on the first years but with little information on business decisions. The company is using a discount rate that is a trade-off between what is normally used in forestry and in industry. Discount rates are critical and need to be looked at with care.

The pulp production has a big impact of the overall sales and profit. However, with different levels of pulp prices, we can still clearly see that the integrated strategy is superior.

Overall NPV increased 1.53-5.21% on average without compromising the sustainability of the forest. These examples show the limit of the decoupled approach which is generally used in forest planning models, and points in the direction of implementing sustainable integrated demand driven VC management strategies.

The case study is relatively simplistic but it clearly shows the superiority of an integrated strategy. The case study is very aggregated in terms of number of products. With a more detailed description, it is likely that the integrated approach will improve even more as it has more alternatives to choose from. To use an integrated approach, we can better decide which areas to harvest to produce the correct levels of logs. Also, we can better decide which bucking patterns to use so it fits the characteristics of the mills. The case also shows that the use of internal transfer prices as coordination mechanisms is not as efficient as it might be believed to be. The MIP model is not much more difficult than the standard forest management problem. This study is a proof that integrated forest companies should work against more integrated planning where the demand information is included.

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