Integrated tactical planning in lumber supply chains

Omid Sanei Bajgiran, Masoumeh Kazemi Zanjani
Department of Mechanical and Industrial Engineering, Concordia University
Montreal, Quebec, Canada

Mustapha Nourelfath
Department of Mechanical Engineering, Faculty of Science and Engineering, Université Laval
Quebec, Canada

Abstract

The problem investigated in this paper is focused on lumber supply chain which is featured as a divergent value chain. In this industry, raw materials (logs) are shipped from forest contractors to sawmills. Then the logs are sawn to finished lumbers and are distributed to the lumber market through different channels. We aim at addressing harvesting, procurement, production, distribution, and sales decisions in an integrated scheme so as to minimize the backlogged orders and the total cost. A mixed integer programming model is proposed to integrate the aforementioned decisions in the lumber supply chain. Three decoupled models are also formulated representing, respectively, harvesting and procurement, production, sales and distribution. The benefit of the integrated model is evaluated by comparing the cost of the integrated model and decoupled models, in a realistic environment by using real data from industry. It is found that substantial improvement can be reached by considering an integrated model.

Key words: Lumber supply chain, Integrated planning, Decoupled planning

1. Introduction

Integrated tactical planning in a supply chain incorporates the synchronized planning of procurement, production, distribution and sale activities, in order to ensure that the customer demand is satisfied by the right product at the right time. Over the last 20 years, much research has been conducted into a partial integration of the functions in a supply chain (SC) due to the difficulty in their complete integration [1]. In divergent-type production systems, several products can be produced after processing a common material. The variable mix of products, in addition to the existence of by-products, make the integration and the coordination of production, procurement, distribution and sales (demand) planning more difficult. Recent studies present the trend of applying Sales & Operation planning (S&OP) into the SC management context in order to coordinate supply chain value creation activities. They consider S&OP as a synchronization mechanism that integrates the demand forecast with supply chain capabilities through coordination of marketing, manufacturing, purchasing, logistics, and financing decisions and activities [2]. Feng et al. [3] presented a modelling approach in order to quantitatively evaluate the impact of S&OP program before implementation.

Wood procurement models can be tracked back to the early 1960s. Since that time, several models have been developed to address different aspects of wood procurement [4]. Some of these models have been designed for specific activities such as skidding or transportation [5,6]. Other models tried to integrate several activities in a single model to capture possible synergies between them. As an instance, Burger and Jannick [7] integrated harvesting, storage, and transportation decisions. To the best of our knowledge, there is no attempt to make these decisions while taking into account production, distribution, and sales decisions.

In literature, there are several contributions focused on lumber production planning. Among them, Maness et al. [8] proposed a mixed programming model to simultaneously determine the optimal bucking and sawing policies based on demand and final product price. Singer et al. [9] presented a model for optimizing planning decisions in the sawmill industry. Their objective was to show the benefit of collaboration by transferring timber and using the competitive advantage of each other. Kazemi Zanjani et al. [10, 11] proposed sawmill production planning models under uncertainty.
In the lumber supply chain which is the main focus of this article, material (logs) flows from forest contractors to sawing facilities. Lumbers and other by-products are then distributed to customers through several channels of distributors. Logs are broken down into different dimensions of lumber by using different cutting patterns. From each log, several pieces of sawn lumbers are produced depending on the cutting pattern. Hence, starting with a single log, several types of lumber with different yields are produced. The latter makes the lumber supply chain a divergent value chain. Briefly, in this paper we aim at integrating harvesting, procurement, production, distribution, and sales decisions in the lumber supply chain so as to maximize the total cost of the supply chain. We also compare the results of the integrated model with two sets of decoupled models.

This paper is organized as follows. The problem description is presented in Section 2, and the mathematical models are formulated in Section 3. Finally, the numerical results and conclusions are presented in Section 4 and 5, respectively.

2. Problem description

Lumber supply chains incorporates forest, as the supplier, sawmills as the manufacturing entities, different distributors, as well as contract and non-contract-based customers. Sawmills purchase logs from forest, and then transform them to lumbers as main products and chips as by-products. There are three main processes in sawmills: sawing, drying, and finishing. In the sawing process, the logs are cut into different sizes of rough lumbers by different cutting patterns. In the drying process, the lumber moisture contents are reduced by large kiln dryers and/or air-drying in order to meet customer requirements. In the finishing process, the lumbers are planned or surfaced, trimmed and sorted based on customer requirements. According to the demand, some logs are sent to the customer immediately after sawing process, while others are sent to drying and finishing processes. The supply chain serves different customers: contract based and noncontract based ones. Contract based customers sign a contract at an agreed price and quantity for a given planning horizon. Although the contract demand must be satisfied, the enterprise reserve the right of postponing or not satisfying some parts of agreed quantity, because of capacity shortage in the demand period. With a non-contract based customer, including spot market, the demand may be not satisfied, when capacity is not available in the demand period. Unsatisfied demand may be served in a future period as backlog. When there is surplus capacity in sawmills, the spot market is sought to absorb remaining capacities.

The purpose of integration is to combine supply chain functions with the goal of increasing efficiencies and reducing costs, and it tries to better connect demand with supply, which can both improve customer service and lower costs. The problem dealt with in this paper is about integrating tactical planning in lumber supply chains that can be stated by the following research questions:

(i) How to integrate all entities of lumber supply chains?

(ii) What are the benefits of the integrated model in comparison with decoupled models in lumber supply chains?

To answer these questions, we first provide a mixed integer programming model that represents the integrated harvesting, procurement, production, distribution and sales planning in the lumber supply chain. Then, we develop two classes of decoupled models. The first class incorporates three decoupled models representing, respectively, harvesting & procurement, production, and distribution & sales decisions. The second class involves two decoupled models representing harvesting & procurement, and production & distribution & sales decisions. In order to highlight the advantage of integrated planning approach, we compare the results of the integrated model with two sets of decoupled models in terms of total cost and revenue in the supply chain.

3. Mathematical models

In this section, we first provide the integrated model, and then we proposed decoupled models as already explained.

3.1 Integrated model

In the integrated model, the objective is to maximize the global net profit by balancing the sales revenue and supply chain cost subject to the aggregated supply chain capacities over a planning horizon $T$. The supply chain costs consist the harvesting, logs procurement, lumber production, and distribution costs. Also, we consider constraints of each entity of lumber supply chain in an integrated fashion.

The indices, sets, parameters, and decision variables used in the proposed models are listed in table 3, 4 and 5 in the appendix.
Model

\[ \text{Max } Z = R - (C_{\text{harvesting}} + C_{\text{stumpage}} + C_{\text{transportation}} + C_{\text{storage}} + C_{\text{procurement}} + C_{\text{production}} + C_{\text{distribution}}) \]  

(1)

Where:

\[ R = \sum_{c} \sum_{i} \sum_{t} b_{ct} S_{ct}^{c} \]  

(2)

\[ C_{\text{harvesting}} = \sum_{bl \in BL} \sum_{t} c_{bl}^{H} y_{blt} \left( \sum_{rm \in RM} v_{rm,bl} \right) \]  

(3)

\[ C_{\text{stumpage}} = \sum_{rm \in RM} \sum_{bl \in BL} \sum_{t} v_{rm,bl} f_{rm,bl,t} y_{blt} \]  

(4)

\[ C_{\text{transportation}} = \sum_{bl \in BL} \sum_{m \in M} \sum_{e} \sum_{t} c_{e}^{T} x_{rm,mt}^{bl} \]  

(5)

\[ C_{\text{storage}} = \sum_{rm \in RM} \sum_{bl \in BL} \sum_{t} c_{rm,blt} s_{rm,blt} \]  

(6)

\[ C_{\text{procurement}} = \sum_{bl \in BL} \sum_{rm \in RM} \sum_{m \in M} \sum_{e} \sum_{t} m_{rtm}^{bl} x_{rm,mt}^{bl} + \sum_{rm \in RM} \sum_{m \in M} \sum_{e} \sum_{t} h_{rm,m}^{t} l_{rm,m}^{t} \]  

(7)

\[ C_{\text{production}} = \sum_{m \in M} \sum_{i} \sum_{l} c_{im} \left( OXSW_{im,t} + OXF_{im,t} \right) + \sum_{m \in M} \sum_{i} \sum_{l} c_{im} \left( h_{1,im}^{t} ISW_{im,t}^{+} \right) + \sum_{m \in M} \sum_{i} \sum_{l} h_{2,im}^{t} IDR_{im,t}^{+} + \sum_{m \in M} \sum_{i} \sum_{l} h_{3,im}^{t} \left( F_{im,t}^{+} - F_{im,t}^{-} \right) + \sum_{m \in M} \sum_{i} \sum_{l} b_{0,im}^{t} ISW_{im,t}^{+} + \sum_{m \in M} \sum_{i} \sum_{l} b_{3,im}^{t} \left( F_{im,t}^{+} - F_{im,t}^{-} \right) \]  

(8)

\[ \sum_{s \in S} \sum_{i} \sum_{r \in R} \sum_{ev} \sum_{t} \left( e_{irv}^{s} X_{irvt}^{s} + sh_{r}^{e} N_{r}^{s} \right) + \sum_{s \in S} \sum_{i} \sum_{d \in DC} \sum_{r \in R,dc} \sum_{ev} \sum_{t} \sum_{trd} X_{irvt}^{s} + \sum_{l \in L} \sum_{d \in DC} \sum_{t} \sum_{hidc} h_{idc} l_{idc}^{t} \]  

(9)

Subject to:

Sales constraints:

\[ S_{ct}^{c} - BS_{ct}^{c} \geq d_{ct}^{c} \quad \forall c \in C, i \in I_{f}, t \]  

(10)

\[ S_{ct}^{c} \leq d_{ct}^{c} \quad \forall c \in C, i, t \]  

(11)

\[ BS_{ct}^{c} \leq S_{ct}^{c} \quad \forall c \in C, i, t \]  

(12)

Harvesting constraints:

\[ \sum_{t} y_{blt} \leq 1 \quad \forall bl \]  

(13)

\[ y_{blt} \leq H_{blt} \quad \forall bl, t \]  

(14)

\[ \sum_{t} H_{blt} \leq l_{bl} \quad \forall bl \]  

(15)

\[ \sum_{bl \in BL} H_{bl,t} \leq n_{t} \quad \forall t \]  

(16)

\[ \sum_{bl \in BL} (G_{blt} \sum_{rm \in RM} v_{rm,bl}) \leq b_{lt}^{t} \quad \forall t \]  

(17)
\[ \sum_{rm \in RM} \sum_{m \in M} \sum_{bl \in BL} x_{rm, m, t}^{bl} \leq b_t^{\bar{r}} \quad \forall t \]  
(18)

\[ l_{rm, bl, 0} = l_{rm, bl, T} = 0 \quad \forall rm, bl \]  
(19)

\[ l_{rm, bl, t} = l_{rm, bl, t-1} - \sum_{m \in M} x_{rm, m, t}^{bl} + v_{rm, bl} y_{bt} \quad \forall rm, bl, t \geq 1 \]  
(20)

Procurement constraints:

\[ \sum_{i \in I_{SW}^c} u_{rm, i, m} OXSW_{int} + \sum_{i \in I_{SW}^c} u_{rm, i, m} XSW_{int} \quad \sum_{i \in I_{SW}^c} u_{rm, i, m} XSW_{int} \quad \forall rm, m, t = 1 + l_{rm}^{bl}, \ldots, T \]  
(21)

\[ l_{rm, m, t} - s_{rm, m} \geq 0 \quad \forall rm, m, t \]  
(22)

\[ \sum_{rm \in RM} l_{rm, m, t} \leq K_{rm, m} \quad \forall rmc, m, t \]  
(23)

\[ \sum_{rm \in RM} \sum_{m \in M} x_{rm, m, t}^{bl} \leq K_{sl}^{bl} \quad \forall bl, t \]  
(24)

\[ \sum_{m \in M} \sum_{rm \in RM} \sum_{t \in T} x_{rm, m, t}^{bl} \geq q_{min}^{bl} \quad \forall bl \]  
(25)

Production constraints:

Sawing process:

\[ \sum_{m \in M} (OXSW_{int} + ISW_{int}^+ - ISW_{int}^- - ISW_{int}^+ + ISW_{int}^-) \leq \sum_{c \in C} S_{ct}^c \quad \forall i \in I_{SW}, t \]  
(26)

\[ \sum_{m \in M} ISW_{int}^- = \sum_{c \in C} B_{ct}^c \quad \forall i \in I_{SW}, t \]  
(27)

\[ \sum_{i \in I_{SW}} p_{int} OXSW_{int} \leq K_{sw} \quad \forall m, t \]  
(28)

\[ \sum_{i \in I_{SW}} ISW_{int}^+ + \sum_{i \in I_{SW}} ISW_{int}^- \leq K_{sw} \quad \forall m, t \]  
(29)

\[ ISW_{int}^- = 0 \quad \forall i \in (I_{SW} \cup I_{SW}', m) \]  
(30)

\[ XSW_{int} + ISW_{int}^+ - ISW_{int}^- = 0 \quad \forall i \in I_{SW}, m, t \]  
(31)

Drying process:

\[ \phi_{int} OXSW_{int} = XDR_{int} \quad \forall i \in I_{SW}, i \in I_{DR}, m, t \]  
(32)

\[ XDR_{int} + IDR_{int}^+ - IDR_{int}^- - IDR_{int}^+ + IDR_{int}^- = 0 \quad \forall i \in I_{DR}, m, t \]  
(33)

\[ \sum_{i \in I_{DR}} p_{int} OXDR_{int} \leq K_{dr} \quad \forall m, t \]  
(34)

\[ \sum_{i \in I_{DR}} IDR_{int}^+ \leq K_{dr} \quad \forall m, t \]  
(35)

\[ IDR_{int}^- = 0 \quad \forall i \in I_{DR}, m \]  
(36)

Finishing process:
\[ p_{i t} \cdot OXDR_{i m t} = OXF_{i m t} \quad \forall i' \in I_{\text{m}}, i \in I_{t}, m, t \]  
\[ \sum_{m \in M} (OXF_{i m t} + IF_{i m t}^{+} - IF_{i m t}^{-} - IF_{i m t}^{-} + IF_{i m t}^{-}) \leq \sum_{c \in c} S_{c t}^{c} \quad \forall i \in I_{t}, m \]  
\[ \sum_{m \in M} IF_{i m t}^{-} = \sum_{c \in c} BS_{c t}^{c} \quad \forall i \in I_{t}, m \]  
\[ \sum_{i \in I_{t}} p_{i \text{int}} \cdot OXF_{i m t} \leq K_{f_{i m t}} \quad \forall m, t \]  
\[ \sum_{i \in I_{t}} IF_{i m t}^{+} \leq K_{I_{m}} \quad \forall m, t \]  
\[ IF_{i m t}^{-} = IF_{i m t}^{-} = 0 \quad \forall i \in I_{t}, m \]

**Distribution constraints:**

\[ \sum_{c \in c}(S_{c t}^{c} + BS_{c t}^{c} - BS_{c t}^{c}) = \sum_{s \in s} \sum_{r \in (R_{m c})} \sum_{v \in V} X_{i t v}^{s} \quad \forall i, t \]  
\[ \sum_{m \in M}(OXSW_{i m t} + ISW_{i m t}^{+} - ISW_{i m t}^{-}) = \sum_{s \in s} \sum_{r \in (R_{m c})} \sum_{v \in V} X_{i t v}^{s} \quad \forall i \in I_{s w}, t \]  
\[ \sum_{m \in M}(OXF_{i m t} + IF_{i m t}^{+} - IF_{i m t}^{-}) = \sum_{s \in s} \sum_{r \in (R_{m c})} \sum_{v \in V} X_{i t v}^{s} \quad \forall i \in I_{t}, m \]  
\[ \sum_{s \in s} \sum_{r \in (R_{m c})} \sum_{v \in V} X_{i t v}^{s} \quad \forall i \in (I_{s w} \cup I_{t}), dc, t \]

\[ N_{i t v}^{s} \geq \sum_{i \in (I_{s w} \cup I_{t})} \frac{a_{i v}^{s} X_{i t v}^{s}}{K_{v}} \quad \forall s \in S, r, v, t \]

\[ \sum_{r \in R} N_{i t v}^{s} \leq K_{S t}^{s} \quad \forall s \in S, v, t \]

\[ \sum_{s \in s} \sum_{r \in (R_{m c})} \sum_{v \in V} N_{i t v}^{s} \leq KD_{m} \quad \forall m, t \]

**Non-negativity constraints:**

\[ S_{c t}^{c}, BS_{c t}^{c}, X_{i t m}, OXSW_{i m t}, ISW_{i m t}, OXDR_{i m t}, XDRI_{i m t}, OXF_{i m t}, XFI_{i m t}, ISW_{i m t}^{+}, IF_{i m t}^{+}, IF_{i m t}^{-}, ISW_{i m t}^{-}, IDR_{i m t}^{-}, IF_{i m t}^{-}, X_{i t v}^{s}, L_{d c t}^{s}, X_{r m d l}^{s}, Y_{b l}, L_{r m b l}, N_{i t v}^{s} \geq 0 \]

\[ H_{b l} \in \{0,1\} \quad \forall c, i, t, m, s, r, v, dc, bl, rm \]

Constraints (10) and (11) describe the sales decisions for contract and non-contract demand. In this case, the demand might be accepted and be served in future periods as backorder (\( l_{\text{int}} \)), or, might be rejected. In either case, the backorder amount (\( BS_{c t}^{c} \)) should not be greater than the sales quantity (\( S_{c t}^{c} \)) (12). Upon satisfaction of the base amount (10), the company may continue serving the contract demand up to the capacity limit, or switch to serve non-contract demand, whichever is more profitable. Constraint (13) ensures that harvested proportion of a block do not exceed the availability of logs in that block. Constraint (14) describes that if harvesting occurs on a block then we can ensure that raw materials from that block are available. Constraints (15) and (16) correspond to the maximum number of harvesting and maximum number of blocks in which harvesting can occur, respectively. Constraints (17) and (18) correspond to harvesting and transportation capacity from each block to each mill, respectively. Constraint (19) represents the initial and final inventory of raw materials in each block. Constraint (20) formulates the inventory balance of raw materials in each block. Constraint (21) determines the quantity of products which should be processed in sawing, drying and finishing units. The raw material safety stock policies are stated in constraint (22) and the raw material inventory capacity constraint is provided in constraint (23). Constraint (24) describes the raw material supply capacity constraints. Constraint (25) states that the material procured from a supplier must satisfy the contract quantity commitment. Constraints (26) and (38) are the coupling constraints that
link the production and sales decisions and determine the maximum amount of production, inventory and backorder in sawing and finishing process for products which are sent to the customer. The backorder quantities are converted into backlogged sales ($BSE_t^c$) (27) and (39), in order to be used in distribution constraints (43). Constraint (28), (34), and (40) formulates the production capacity constraints in sawing, drying, and finishing units. Constraint (29), (35), and (41) define the warehouse inventory capacity in sawing, drying, and finishing units. The beginning and ending backlog conditions in sawing, drying, and finishing units for both classes of products are described in constraints (30), (36), and (42). Constraint (31) is a flow conservation constraint for consumed product, inventory and backorder, and calculates the output quantity of products from the sawing unit. Constraint (32) ensures that the total amount of green lumber sawn by the sawing unit should be processed in the drying unit with a specific yield. Constraint (33) links the quantities of green lumber received from the sawing process, the inventory and backorder, and quantity of dried lumbers. Constraint (37) ensures that the total amount of dried lumbers received from the drying unit will be processed in the finishing unit by considering a specific yield. Constraint (43) links the sales and distribution decisions. Constraints (44) and (45) link the production and distribution decisions. Constraint (46) is the flow balance constraints at a distribution center. Constraint (47) calculates the number of truckload requirements for each vehicle type from each shipping supplier. Constraint (48) and (49) formulate the shipping supplier capacity and the mill dispatch capacity constraints, respectively.

3.2 Decoupled models

In this section, two classes of decoupled models are considered. The first one considers three sub-models including sales & distribution, production, and harvesting & procurement, and the second one considers two sub-models including sales & distribution & production, and harvesting & procurement. To solve each sub-model, it is necessary to add extra constraints to link sub-models to each other and ensure the feasibility of each model. Although we solve each sub-model separately, we link them by adjusting their inputs. More precisely, the output of one sub-model is the input of another one. For instance, the output of sales & distribution sub-model is the input of production sub-model. Also it is necessary to add extra constraints in order to ensure the feasibility of each sub-model.

Sales & distribution sub-model

The objective of this model is to maximize the total revenue from sales activities minus the distribution costs as follows:

$$\text{Max } z = \sum_{c \in C} \sum_{l \in L} \sum_{t \in T} \hat{h}_{lt}^c S_{lt}^c - \sum_{s \in S} \sum_{l \in L} \sum_{d \in DC} \sum_{r \in P} \sum_{v \in V} \sum_{t \in T} (e_{tv}^l X_{tv}^l + s h_{tv}^l N_s^t) - \sum_{s \in S} \sum_{l \in L} \sum_{d \in DC} \sum_{r \in P} \sum_{v \in V} \sum_{t \in T} tr_{idc} X_{idc}^s - \sum_{i \in I} \sum_{l \in L} \sum_{d \in DC} \sum_{t \in T} h_{idc} l_{idct}$$

(51)

The constraints of this model include constraints (10-12) and (43, 46, 47, 48, 49, 50) in the integrated model plus the following ones:

$$\sum_{i \in I_F} S_{lt}^c \leq \sum_{m \in M} K_{fmt} \quad \forall t$$

(52)

$$\sum_{i \in I_{SW}} S_{lt}^c \leq \sum_{m \in M} K_{swnt} \quad \forall t$$

(53)

Constraints (52) and (53) enforce the sales and distribution model to control the amount of the sales quantity of each product based on the production capacity of sawing and finishing units. These two constraints are added to the decoupled model in order to ensure the feasibility of promised sales amount to the customer.

Production sub-model

The objective of this model is to minimize the production, inventory, and backlog costs at sawing, drying, and finishing units. Also, this model works based on the sales and distribution decision ($S_{lt}^c, l_{idct}$) as parameters (input) from the sales & distribution sub-model. This model is as follows:

$$\text{Min } z = \sum_{m \in M} \sum_{l \in L} \sum_{t \in T} c_{lm} (OXSW_{lmt} + OXF_{lmt}) + \sum_{m \in M} \sum_{l \in L} \sum_{t \in T} h_{lm} IDR_{lmt}^* + \sum_{m \in M} \sum_{l \in L} \sum_{t \in T} h_{3lm} IDR_{lmt}^* + \sum_{m \in M} \sum_{l \in L} \sum_{t \in T} h_{1lm} I_{lmt}^* + \sum_{m \in M} \sum_{l \in L} \sum_{t \in T} h_{2lm} I_{lmt}^* + \sum_{m \in M} \sum_{l \in L} \sum_{t \in T} h_{6lm} I_{lmt}^*$$

(54)

The constraints of this model involve constraints (26) – (42) in the integrated model plus the following ones:
Harvesting & procurement sub-model
The constraints of this model are the same as constraints (13-25) in the integrated model.

Product is shipped to 140 customers by 4 outbound shipping suppliers using 5 different vehicle types with via 2

4. Numerical results
In order to validate the integrated tactical planning model proposed in the context of a lumber supply chain, we need a data set that sufficiently represents a realistic scale sawmill in Canada. The realistic environment which we are studying in this paper consists two sawmills producing 27 product families with using 14 types of raw materials. Products are shipped to 140 customers by 4 outbound shipping suppliers using 5 different vehicle types with via 2 distribution centers and 20 routes. Also, we assumed that 50 harvesting blocks are available in the forest during the 12 month planning horizon. The case study defined in this paper results nearly 270,000 continuous and 600 binary

Table 1. Comparison of integrated and decoupled models (class 1)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Models</th>
<th>Integrated model</th>
<th>Decoupled model</th>
<th>Δ over class 1</th>
<th>Deviation over class 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total revenue</td>
<td></td>
<td>1,135,091,368</td>
<td>1,146,102,353</td>
<td>-11,010,985</td>
<td>-1%</td>
</tr>
<tr>
<td>Distribution cost</td>
<td>Inventory</td>
<td>1,082,233,755</td>
<td>1,013,088,646</td>
<td>-69,145,109</td>
<td>-6%</td>
</tr>
<tr>
<td></td>
<td>Transshipment</td>
<td>8,683</td>
<td>9,313</td>
<td>630</td>
<td>7%</td>
</tr>
<tr>
<td>Inventory cost</td>
<td></td>
<td>8,682,339</td>
<td>74,460,686</td>
<td>65,778,347</td>
<td>88%</td>
</tr>
</tbody>
</table>
In table 1, we can see the total revenue in decoupled model is greater than the integrated one. It means that the promised sales in the decoupled model are greater and more overestimated than the integrated one. Because in the decoupled model, sales & distribution and production models are considered separately, the inventory and backorder quantity and their costs in decoupled model are much higher than the integrated model in order to satisfy the bigger amount of promised sales, consequently a big $\Delta$ in inventory and backorder cost can be observed in table 1. On the other hand, in the integrated model, because sales & distribution and production sub-models are considered in an integrated scheme, there is not any backlogged product, and the inventory is much less, and also the production quantity is greater than the decoupled one; consequently the harvesting and procurement quantity and costs of raw material become greater in the integrated model. Although the total revenue in decoupled model is greater and the distribution, procurement and harvesting costs are less than the integrated one, nevertheless the huge amount of inventory and backlog quantity and costs in the production sub-model cause the total profit in the integrated model becomes greater than the decoupled one, and a 41% improvement in the total profit is concluded.

Table 2 summarizes the comparison of the integrated model with the decoupled model (class 2). As expected, the integrated model generates the highest profit in comparison with the decoupled model. In this case, the benefit of the integrated model over class 2 is relatively moderate because of the improved performance with integrating production model with the sales & distribution one (41% vs 14%).

In benefit evaluation of the integrated model with decoupled models, we observed that although the revenue in case 1 was greater than the integrated model, but the integrated model made further modifications on sales decisions, that although overall revenue was reduced, total cost specially including the total inventory and backorder costs was reduced more significantly resulting in a net profit improvement. Also, in case 2 the actual revenue was the same, but the total costs were greater in decoupled model resulting the total profit became greater in the integrated model in comparison with the decoupled one. But, the profit improvement in case 2 was relatively moderate because of the improved performance with integrating production model with the sales and distribution one.

5. Conclusions
In this paper, we addressed harvesting, procurement, production, distribution, and sales decisions in lumber supply chain in an integrated scheme so as to maximize the total profit. A mixed integer programming model was proposed to integrate the aforementioned decisions. Also, three decoupled models were also formulated representing, respectively, harvesting and procurement, production, sales and distribution. The benefit of the integrated model was evaluated by comparing the integrated model and decoupled models in terms of total revenue and costs in a realistic

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Integrated model</th>
<th>Decoupled model</th>
<th>$\Delta$ over class 2</th>
<th>Deviation over class 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total revenue</td>
<td>1,135,091,368</td>
<td>1,135,091,368</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Distribution cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inventory</td>
<td>1,082,233,755</td>
<td>1,088,537,212</td>
<td>6,303,457</td>
<td>1%</td>
</tr>
<tr>
<td>Transshipment</td>
<td>8,683</td>
<td>8,992</td>
<td>309</td>
<td>4%</td>
</tr>
<tr>
<td>Inventory cost</td>
<td>8,682,339</td>
<td>7,476,906</td>
<td>-1,205,433</td>
<td>-14%</td>
</tr>
<tr>
<td>Backlog cost</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Production cost</td>
<td>5,461,405</td>
<td>5,432,777</td>
<td>-28,628</td>
<td>-1%</td>
</tr>
<tr>
<td>Harvesting cost</td>
<td>1,117,781</td>
<td>1,077,037</td>
<td>-40,744</td>
<td>-4%</td>
</tr>
<tr>
<td>Procurement cost</td>
<td>1,142,521</td>
<td>1,111,861</td>
<td>-30,660</td>
<td>-3%</td>
</tr>
<tr>
<td>Total profit</td>
<td>36,444,883</td>
<td>31,446,583</td>
<td>4,998,300</td>
<td>14%</td>
</tr>
</tbody>
</table>

Table 2. Comparison of integrated and decoupled models (class 2)
environment based on industrial data. It is found that substantial improvement can be reached by considering an integrated model, instead of a decoupled model. Future research will consider uncertainty into the proposed integrated model.

Appendix

Table 3. Sets

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{SW}$</td>
<td>Set of products produced by sawing process that are transferred to drying unit (such as lumbers)</td>
</tr>
<tr>
<td>$l'_{SW}$</td>
<td>Set of products produced by sawing process (such as chips and green lumbers)</td>
</tr>
<tr>
<td>$l_{DR}$</td>
<td>Set of products produced by drying process</td>
</tr>
<tr>
<td>$l_E$</td>
<td>Set of products produced by sawing, drying and finishing processes (such as finished product)</td>
</tr>
<tr>
<td>$I$</td>
<td>Set of end products ($I = l'_{SW} \cup l_E$)</td>
</tr>
<tr>
<td>$R_{m,dc}$</td>
<td>Set of routes from mills to distribution centers</td>
</tr>
<tr>
<td>$R_{dc,c}$</td>
<td>Set of routes from distribution centers to customers</td>
</tr>
<tr>
<td>$R_{m,c}$</td>
<td>Set of routes from mills to customers directly</td>
</tr>
</tbody>
</table>

Table 4. Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{it}$</td>
<td>Unit production cost to produce product $i$ at mill $m$ in period $t$</td>
</tr>
<tr>
<td>$d_{it}$</td>
<td>Inventory holding cost for unit quantity of product $i$ in period $t$</td>
</tr>
<tr>
<td>$e_{im}$</td>
<td>Expedtion capacity of mill $m$</td>
</tr>
<tr>
<td>$h_{im}$</td>
<td>Volume of raw material available on block $i$ during period $t$</td>
</tr>
<tr>
<td>$r_{im}$</td>
<td>Inventory capacity of raw material category $r$ at mill $m$</td>
</tr>
<tr>
<td>$V_i$</td>
<td>Total harvesting and transportation capacity in period $t$</td>
</tr>
<tr>
<td>$K_{SW,m}$</td>
<td>Production capacity of mill $m$ in period $t$ at sawing, drying and finishing units</td>
</tr>
<tr>
<td>$Kd_{R,m,t}$</td>
<td>Vehicle capacity absorption coefficient per unit of product $i$ using vehicle type $v$</td>
</tr>
<tr>
<td>$Kf_{R,m,t}$</td>
<td>Supply capacity of block $bl$ in period $t$</td>
</tr>
<tr>
<td>$KSH_{sv}$</td>
<td>Shipping capacity of supplier $s$ with vehicle $v$</td>
</tr>
<tr>
<td>$Kv$</td>
<td>Capacity of vehicle type $v$</td>
</tr>
<tr>
<td>$KD_m$</td>
<td>Supply capacity of block $bl$ in period $t$</td>
</tr>
<tr>
<td>$K_{R,m,t}$</td>
<td>Lead time of procuring raw material $rm$ from block $bl$</td>
</tr>
<tr>
<td>$m_{R,m,t}$</td>
<td>Unit purchase cost of raw material $rm$ from block $bl$ in period $t$</td>
</tr>
<tr>
<td>$h_{R,m,t}$</td>
<td>Inventory holding cost of raw material $rm$ at mill $m$</td>
</tr>
<tr>
<td>$l_{R,m,t}$</td>
<td>Average yield of product $i$ from block $bl$ during period $t$</td>
</tr>
<tr>
<td>$s_{R,m,t}$</td>
<td>Minimum contract purchase quantity from block $bl$</td>
</tr>
<tr>
<td>$SS_{R,m,t}$</td>
<td>Safety stock of raw material $rm$ at mill $m$</td>
</tr>
<tr>
<td>$n_t$</td>
<td>Maximum number of periods over which harvesting can occur in block $bl$</td>
</tr>
<tr>
<td>$\n_t$</td>
<td>Maximum number of blocks in which harvesting can occur during period $t$</td>
</tr>
<tr>
<td>$\nu_{R,m,t}$</td>
<td>Volume of raw material $rm$ available on block $bl$</td>
</tr>
<tr>
<td>$b_{t}^{0}, b_{t}'$</td>
<td>Unit cost to harvest block $bl$ during period $t$</td>
</tr>
<tr>
<td>$\nu_{R,m,t}$</td>
<td>Unit cost to store raw material $rm$ on block $bl$ during period $t$</td>
</tr>
<tr>
<td>$f_{R,m,t}$</td>
<td>Stumpage fee for raw material $rm$ on block $bl$ during period $t$</td>
</tr>
<tr>
<td>$c_{R,m,t}$</td>
<td>Unit cost to transport raw material $rm$ from block $bl$ to mill $m$ during period $t$</td>
</tr>
</tbody>
</table>
Table 5. Decision variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{bl,rm,m,t}$</td>
<td>Purchasing quantity of raw material $rm$ from block $bl$ by mill $m$ in period $t$</td>
</tr>
<tr>
<td>$I_{bl,rm,m,t}$</td>
<td>Inventory of raw material $rm$ at mill $m$ at the end of period $t$</td>
</tr>
<tr>
<td>$I_{bl,rm,m,t}$</td>
<td>Inventory of raw material $rm$ in block $bl$ at the end of period $t$</td>
</tr>
<tr>
<td>$y_{hit}$</td>
<td>Proportion of harvested block $bl$ in period $t$</td>
</tr>
<tr>
<td>$H_{hit}$</td>
<td>Binary variable (if harvesting occurs on block $bl$ during time period $t$)</td>
</tr>
<tr>
<td>$OXW_{int}$</td>
<td>Quantity of product $i$ that should be transferred from sawing unit of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$XSW_{int}$</td>
<td>Quantity of product $i$ which should be sawn at sawing unit of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$XDR_{int}$</td>
<td>Quantity of product $i$ which should be processed at drying unit of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$OXDR_{int}$</td>
<td>Quantity of product $i$ which should be transferred from drying to finishing unit of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$OXF_{int}$</td>
<td>Quantity of product $i$ which should be transferred from finishing unit of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$ISW_{int}^r, IDR_{int}^s, IF_{int}^t$</td>
<td>Inventory quantity of product $i$ at sawing, drying and finishing units of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$ISW_{int}^r, IDR_{int}^s, IF_{int}^t$</td>
<td>Backlog quantity of product $i$ at sawing, drying and finishing units of mill $m$ in period $t$</td>
</tr>
<tr>
<td>$X_{i,s,rvt}^c$</td>
<td>Shipping quantity of product $i$ with shipping supplier $s$ on route $r$ with vehicle $v$ in period $t$</td>
</tr>
<tr>
<td>$I_{dc}^c$</td>
<td>Inventory quantity of product $i$ in distribution center $dc$ at the end of period $t$</td>
</tr>
<tr>
<td>$N_{rvt}^c$</td>
<td>Number of truckload requirement from shipping supplier $s$ on route $r$ with vehicle $v$ in period $t$</td>
</tr>
<tr>
<td>$S_{it}^c$</td>
<td>Sales quantity of product $i$ to customer $c$ in period $t$</td>
</tr>
<tr>
<td>$BS_{it}^c$</td>
<td>Backlog quantity of product $i$ to customer $c$ in period $t$</td>
</tr>
</tbody>
</table>

References