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Article

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OPERATIONS, INFORMATION & TECHNOLOGY | RESEARCH ARTICLE

Optimal production-inventory model for forest products industry supply chain under demand and supply uncertainty: Case study of a pulp mill in Ontario

Shashi Shahi^{1*}, Reino Pulkki¹, Mathew Leitch¹ and Christopher Gaston²

Abstract: The production planning models used in the forest products industry do not recognize the demand and supply uncertainty, and as such do not work in unison with the inventory management models. An integrated production planning and inventory management model of a forest products industry is developed in this paper. The objective is to maximize the net annual profit of the forest industry under demand and supply uncertainty. The model is formulated as a simulation-based optimization model. A case study of a pulp mill in Northwestern Ontario shows that supply and demand uncertainty causes a net annual loss of \$59.9 million to the pulp mill, whereas the introduction of a merchandizing yard in the supply chain not only absorbs shocks caused due to uncertainty, but also increases the net annual profit of the pulp mill to \$26.7 million. However, the merchandizing yard is viable only if the sales price of pulp is above a threshold level. The integrated supply chain model can be applied to any forest products industry as it considers the entire supply chain structure and manages all business decisions both upstream and downstream in the supply chain.

ABOUT THE AUTHORS

The main emphasis of my research has been on developing optimization model for the Canadian forest industry supply chain. I use simulation-based optimization approach that integrates the two-way flow of information and materials under stochastic supply and demand of the Canadian forest products industry. My supply chain management models provide real-time operations management decision support tools both for single products (sawmills and pulp) industry and for multi products (lumber, pulp, bioenergy, and combined heat and power) forest industry. The decision support systems constantly share information among all agents in the supply chain network. The flow of information starts from market demand and tracks back up the supply chain through all facilities including retailers, wholesalers, secondary and primary producers, merchandizing yard, and suppliers. My major research contribution has been the incorporation of merchandizing yard in the supply chain that handles supply and demand uncertainty in the Canadian forest industry.

PUBLIC INTEREST STATEMENT

The Canadian forest products industry is operating under uncertain supply of wood fiber from the forest management units and uncertain demand of forest products from the customers. Under these stochastic supply and demand conditions, the forest industries are unable to operate at full capacity production, and are spending a substantial portion of their costs in managing their inventory. An optimal production-inventory model is developed for the Canadian forest products industry that manages all inventory planning decisions, both upstream and downstream in the supply chain, in the presence of continuously changing information across the entire supply chain. A merchandizing yard, included between the suppliers and the pulp mill, absorbs supply and demand shocks, ensures continuous production of the pulp mill, as well as improves customer satisfaction. However, the merchandizing yard is viable only if the sales price of pulp is above a threshold level.

Subjects: Operations Research; Production Systems; Manufacturing & Processing; Operations Management; Production Research & Economics; Operational Research/ Management Science; Supply Chain Management

Keywords: forest products industry; simulation-based optimization; supply uncertainty; demand uncertainty; supply chain management

1. Introduction

The production planning models of forest products industry supply chains do not recognize the supply and demand uncertainty and generate inferior operational management decisions (D'Amours, Rönnqvist, & Weintraub, 2008). The Canadian forest products industry¹ supply chains are characterized by complex network of suppliers, forest products mills, and distributors, and the inventory stockpiles with each agent affect the overall performance and cost of the entire supply chain. These inventories can cost up to 40% of the total annual cost under uncertain supply and demand (Ganeshan, 1999). Therefore, the inventory management system needs coordinated decisions about inventory levels at each location in the supply chain (Lee & Billington, 1992). This will help the forest products industry to change their input/output activities according to market signals and minimize the loss caused due to frequent interruptions in supply. Moreover, the varied activities of the forest products industry supply chain agents makes the task of integrating the procurement, production, distribution and sales management very complex, given that these activities are always bounded by trade-offs between reducing logistics costs and improving customer satisfaction (Carlsson, D'Amours, Martel, & Ronnqvist, 2008; Shahi & Pulkki, 2013a; Weintraub & Romero, 2006).

The operational planning decisions (e.g. harvesting, production scheduling, inventory management, and transportation planning) in the forest products industry supply chain are reliant on demand and supply, which in turn are highly stochastic in nature (Church, 2007; Fahimnia, Farahani, Marian, and Luong, 2013; Gaudreault, Frayret, Rousseau, & D'Amours, 2011). The restriction in supply affects the production and hence the customer satisfaction, which can only be achieved if the right kinds of products are delivered to the customers in the right quantity and at the right time (Alonso-Ayuso et al., 2003). Interest in merchandizing yards has increased in the forest products industry in response to uncertainty in supply and the need to recover more value from the available resource (Dramm, Govett, Bilek, & Jackson, 2004; Dramm, Jackson, & Wong, 2002). The merchandizing yard helps in enhancing the value of trees removed from forests by effectively evaluating and sorting wood fiber into saw logs, stud logs, peeler logs, post and pole, pulpwood and hog fuel for quality and highest value recovery before delivery to the forest products industry (Han, Bilek, Dramm, Loeffler, & Calkin, 2009). However, the performance of merchandizing yards in forest products industry supply chain has not been evaluated so far, due to complexity of the problem involving multiple-products and multiple-agents. The complex supply chain optimization problem is solved using simulation-based optimization models, which allow the decision-makers to see the performance of the supply chain over time under various scenarios and help them understand the inter-relationships between different model components (Bredström et al., 2004; Jung, Blau, Pekny, Reklaitis, & Eversdyk, 2004; Shahi & Pulkki, 2013b). Although, simulation-based optimization models have been used for supply chain management in the manufacturing industries, (Esmaeilikia et al., 2014, Fu, 2002; Mele, Guillén, Espuña, & Puigjaner, 2006), there is no such model that integrates operational planning with inventory management decision of supply chain agents in the forest products industry under demand and supply uncertainty.

The purpose of this paper is to develop a simulation-based optimization model for integrating production planning with inventory management in the forest products industry supply chain under supply and demand uncertainty. The simulation-based optimization model is then used as a case study for integrating the production planning and inventory management of a pulp mill supply chain in Northwestern Ontario in Canada. The model analyzes the effects of supply and demand uncertainty on: (i) net annual profit of a pulp mill and (ii) the performance of a merchandizing yard in managing risks associated with supply and demand uncertainty.

2. Methodology

In order to create an integrated production planning and inventory management model, first the wood fiber flow in the forest products supply chain is understood. A simulation model for the forest industry (a pulp mill as a case study) supply chain is then developed, where the flow of material is based on the wood fiber supply from the forest management units, production capacity of the pulp mill, and demand of forest products in the domestic and international markets. Based on historical data for the supply and demand of forest products, we used probability distributions to account for short-term supply and demand uncertainty. The long-term supply and demand uncertainty is analyzed by simulating supply restrictions by different suppliers and varying demand in domestic and export markets for longer periods of time (Carlsson and Rönnqvist, 2005). Each agent in the supply chain has two ports, the receiving port and the supply port, where the inventory management decisions are to be made. The simulation model is then integrated with an optimization model, which uses a meta-heuristic algorithm to evaluate the statistical outputs from the simulation model, and finds global optimum solutions. The integrated simulation-based optimization model is then used for analyzing the effects of supply and demand uncertainty on net annual profit of the pulp mill, and in managing risks associated with supply and demand uncertainty of the pulp mill.

The supply chain model follows stationary (s, S) inventory policy, which is a minimum/maximum inventory policy, for all agents. The re-order point in this inventory policy is the level s , and the re-order quantity restores the inventory back to the level S . It is assumed that the supplies are instantly received and there is no delay. Each agent starts with a beginning inventory level (I_{beg}) and beginning backlog order position (BL_{beg}) for each month. The agent compares its beginning backlog position with the difference between the beginning inventory level and minimum inventory level (s), and calculates the initial backlog order position at time t (BL_t) as in Equation (1):

$$BL_t = \begin{cases} BL_{beg} - (I_{beg} - s) & \text{if } BL_{beg} \geq I_{beg} - s \\ 0 & \text{if } BL_{beg} < I_{beg} - s \end{cases} \quad (1)$$

As the supply of material (S_t) is received from the upstream agent in respect of the previous month's order, the agent updates its new inventory level (I_t) for the month t as in Equation (2):

$$I_t = I_{t-1} + S_t \quad (2)$$

Next the agent checks its demand received (D_{t-1}) from the downstream agents in the previous month, and updates the new demand (D_t) by adding the initial backlog order position (BL_t) as in Equation (3):

$$D_t = D_{t-1} + BL_t \quad (3)$$

The quantity supplied (Q_t) to the downstream agent is decided by comparing the new inventory level (I_t) with the sum of new demand and minimum inventory level ($D_t + s$) as in Equation (4). The quantity supplied is 0 if $I_t < s$.

$$Q_t = \begin{cases} D_t & \text{if } I_t > D_t + s \\ I_t - s & \text{if } I_t \leq D_t + s \end{cases} \quad (4)$$

The model then updates the ending inventory level (I_{t+1}) and ending backlog order position (BL_{t+1}) of the supply chain agent as in Equations (5) and (6), respectively.

$$I_{t+1} = I_t - S_t \quad (5)$$

$$BL_{t+1} = D_t - S_t \quad (6)$$

Finally, one order for supply (O_t) per month is placed to the upstream agent based on inventory levels (s, S) as in Equation (7):

$$O_t = \begin{cases} 0 & \text{if } I_{t+1} \geq s \\ S - I_{t+1} & \text{if } I_{t+1} < s \end{cases} \quad (7)$$

The total annual ordering cost of the pulp mill receiving unit is given in Equation (8).

$$O_{\text{pulpmill}(ru)} = \sum_{t=1}^{12} O_{\text{pulpmill}(ru)}(t) \quad (8)$$

where, $O_{\text{pulpmill}(ru)}(t)$ is the ordering cost incurred in the t^{th} month by the pulp mill receiving unit. Let $I^+(t) = \max\{-I(t), 0\}$ be the amount of volume physically on hand in the inventory at time t , and $I^-(t) = \max\{-I(t), 0\}$ be the backlog at time t , where $I(t)$ is the inventory level at the pulp mill receiving unit at time, t (in months), which could be positive, negative, or zero. If the pulp mill receiving unit incurs a holding cost of $ho_{\text{pulpmill}(ru)}$ per m^3 per month, a handling cost of $ha_{\text{pulpmill}(ru)}$ per m^3 per month held in (positive) inventory, and a shortage cost of $v_{\text{pulpmill}(ru)}$ per m^3 per month for the backlogged orders in (negative) inventory, then the total annual holding, handling and shortage cost of pulp logs for the pulp mill receiving unit are, respectively, given by Equation (9):

$$\begin{aligned} HO_{\text{pulpmill}(ru)} &= \sum_{t=1}^{12} ho_{\text{pulpmill}(ru)}(t)I^+ \\ HA_{\text{pulpmill}(ru)} &= \sum_{t=1}^{12} ha_{\text{pulpmill}(ru)}(t)I^+ \\ V_{\text{pulpmill}(ru)} &= \sum_{t=1}^{12} v_{\text{pulpmill}(ru)}(t)I^- \end{aligned} \quad (9)$$

Finally, the total annual cost for the pulp mill receiving unit, $TC_{\text{pl}(ru)}$ is given in Equation (10):

$$TC_{\text{pl}(ru)} = O_{\text{pulpmill}(ru)} + HO_{\text{pulpmill}(ru)} + HA_{\text{pulpmill}(ru)} + V_{\text{pulpmill}(ru)} \quad (10)$$

Using the same logic, the total annual cost for the pulp mill supply unit $TC_{\text{pl}(su)}$ is obtained from the model. The supply unit also incurs a transportation cost for shipping pulp to the downstream mills, which occurs in the same period, given by Equation (11):

$$TR_{\text{pulp}} = \sum_{t=1}^{12} tr_{\text{pulp}}(t)Q_{\text{pulp}} \quad (11)$$

where, the pulp mill supplies Q_{pulp} tonnes of pulp per month to the paper and textile mills, and incurs a transportation cost of tr_{pulp} per tonne. The total annual cost for the pulp mill supply unit, $TC_{\text{pl}(su)}$ is given by Equation (12):

$$TC_{\text{pl}(su)} = O_{\text{pulpmill}(su)} + HO_{\text{pulpmill}(su)} + HA_{\text{pulpmill}(su)} + V_{\text{pulpmill}(su)} + TR_{\text{pulp}} \quad (12)$$

The total annual production cost for the pulp mill is calculated from the total production, Pr_{pulp} tonnes of pulp per month, and production cost of pc_{pulp} per tonne, using the Equation (13):

$$PR_{\text{pulp}} = \sum_{t=1}^{12} pr_{\text{pulp}}(t)pc_{\text{pulp}} \quad (13)$$

The costs in Equations (10), (12), and (13) are added together to obtain the total annual cost, TC_{pl} for the pulp mill, given in Equation (14):

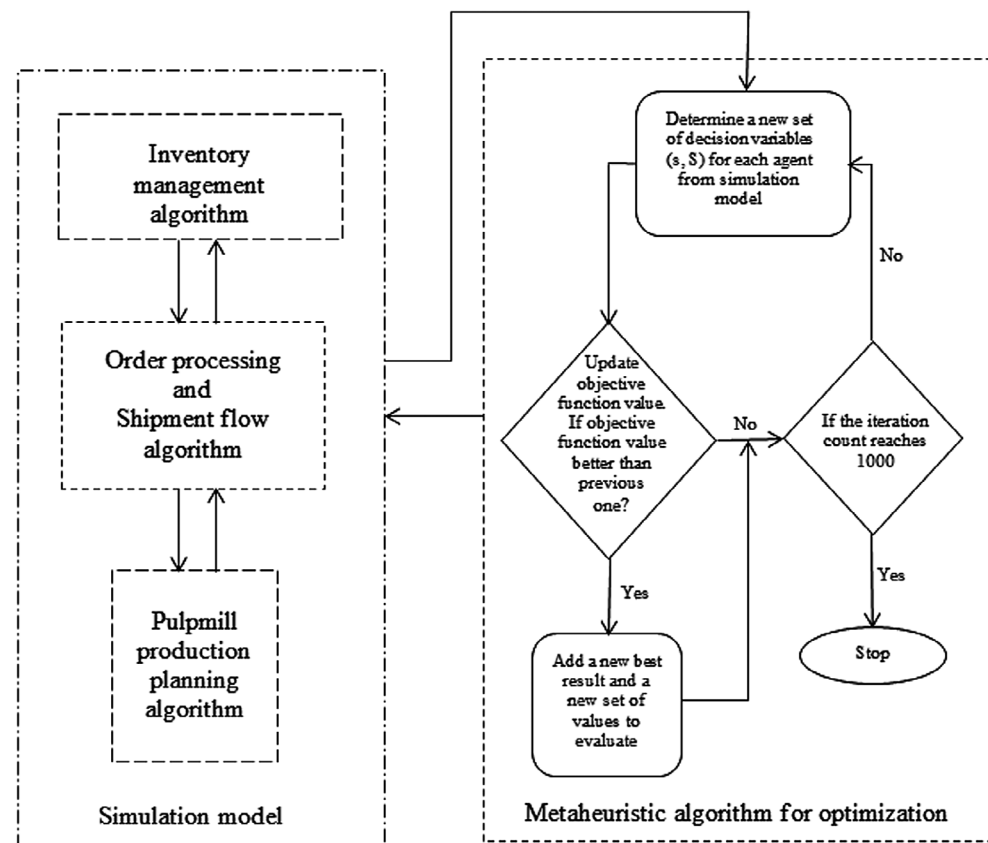
$$TC_{pl} = TC_{pl(ru)} + TC_{pl(su)} + PR_{pulp} \tag{14}$$

The total annual costs of other supply chain agents are calculated in the same manner as explained for the pulp mill, except for supplier, where harvesting costs are also added.

The simulation model itself does not prescribe an optimal solution for the integrated production planning and inventory management problem, and requires integration with an optimization approach. Traditional search methods for an optimal solution work well when finding local solutions around a given starting point with model data that are precisely known. However, these methods fail when searching for global solutions to real world problems that contain significant amounts of uncertainty. Recent developments in optimization have produced efficient search methods capable of finding optimal solutions to complex problems involving uncertainty (Kokash, 2005). An OptQuest engine optimization solver that uses meta-heuristic search algorithm guides the search for optimum solutions (Olafsson, 2006). OptQuest incorporates meta-heuristics to guide its search algorithm toward better solutions, using a form of adaptive memory to remember the solutions that worked well before and recombines them into new and better solutions. Since this technique does not use the hill-climbing approach of ordinary solvers, it is neither trapped in local solutions nor thrown off course by uncertain model data. Figure 1 shows the overall flowchart of the simulation-based optimization process of the integrated supply chain model. The objective function of the optimization model is to maximize the net annual profit (NAP) of the pulp mill. Mathematically, the objective function is given in Equation (15):

$$NAP = \sum_{t=1}^{12} P \times Q_t - (tC_{pl(ru)t} + tC_{pl(su)t} + pR_{pulp_t}) \tag{15}$$

Figure 1. Overall flow chart of the simulation-based optimization process in the integrated supply chain model.



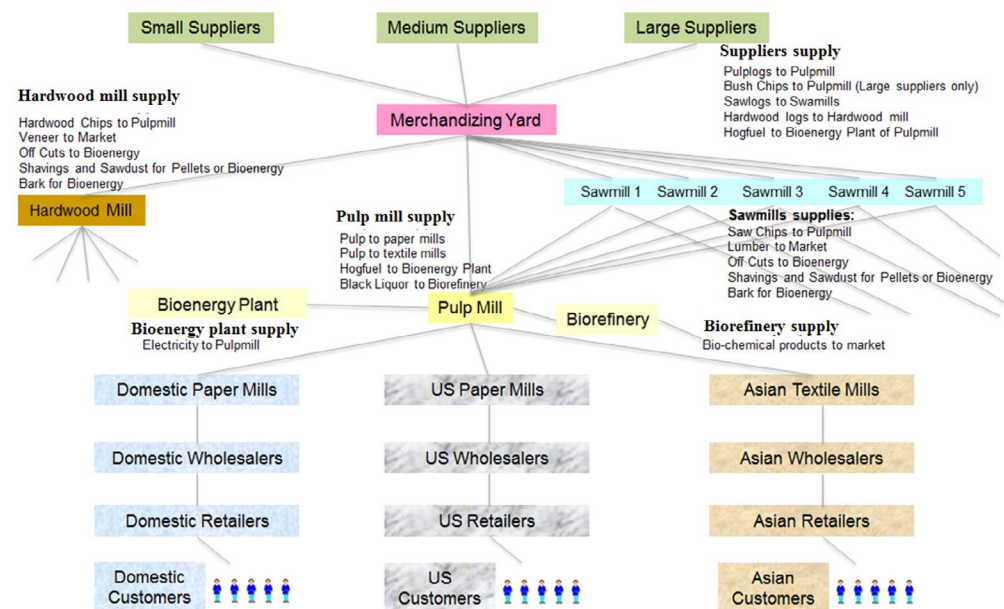
where; $t = 1, \dots, 12$ indicate 12 months of the year. P is the sale price of pulp (\$/tonne), Q_t is the total monthly quantity (tonnes) of pulp supplied by the pulp mill, $tC_{pl_{r_{uit}}}$ is the total monthly supply chain cost of the pulp mill receiving unit, $tC_{pl_{s_{uit}}}$ is the total monthly supply chain cost of the pulp mill supply unit, pR_{pulp_t} is the total monthly production cost of the pulp mill, such that a specified customer satisfaction level is achieved. The capacity-feasible requirements in the optimization model are that if the demand of pulp or supply of pulp logs for certain month is less than 5% of full running capacity of the pulp mill, there is no production of pulp in that month. The decision variables for this optimization model are order quantity, inventory parameters (s, S), and supply quantity of all supply chain agents. The constraints (S is always greater than s for each supply chain agent) are used in the optimization process.

The meta-heuristic algorithm iteratively evaluates statistical outputs (net annual profit for the pulp mill and total cost for each agent in the supply chain) from the simulation model, analyzes and integrates these outputs with those obtained from previous simulation runs, and determines a new set of values to evaluate. This iterative process provides a highly efficient trajectory to the best solutions. The search process continues until meta-heuristic algorithm reaches some termination criteria, in this case a maximum number of simulations (1,000 iteration counts). For each simulation, 10 replications are run, and each run of the simulation model takes about 30–40 min. Optimization was performed using Intel® Core™ i7 CPU with 8 GB RAM.

3. Case study of a pulp mill

Forest products supply chains have large networks through which wood fiber from the forest is transformed into products demanded by the customer. Figure 2 illustrates a multi-industry forest products supply chain, with a pulp mill as the nodal agent, and a proposed merchandizing yard between the suppliers and the mills. On the upstream side of the pulp mill, the production network is linked to a procurement network that starts in the forest management unit, and on the downstream side of the pulp mill, the production network is linked to a distribution network that ends with the customers. The network involves suppliers, providing a set of products to multiple industries (pulplogs and wood chips to pulp mill, saw logs to sawmills, hardwood logs to hardwood mills, and hog fuel to bioenergy plants). The pulp mill supplies pulp to paper and textile mills, which fulfill demands at multiple customer locations through wholesalers and retailers. Different modes of transportation (trucks and trains) are used to transport forest products from one agent to the other in the supply chain. At each stage of the production process, some by-products are produced along with the main

Figure 2. Integrated supply chain model of pulp mill with merchandizing yard.



products. For example, wood chips produced in the sawmills are re-used in the pulp mill for producing pulp, whereas black liquor from the pulp mill is used in biorefineries (Bowyer, Shmulsky, & Haygreen, 2003).

The pulp mill needs a regular supply of wood fiber (pulp logs) for un-interrupted production of pulp under both stochastic supply and demand conditions. The supply of pulp logs to the pulp mill is done by three categories of suppliers (small, medium and large), who supply 18, 36, and 46% of the annual demand of the pulp mill, respectively. Although, there is a known average annual rate of pulp logs that the suppliers supply to the pulp mill, there is huge variability in monthly supply. Supply uncertainty in the wood fiber supply network is not only caused by random variation in the business-as-usual (BAU) scenario, but extreme events such as natural disasters (fire or blow down), weather conditions, and operational problems associated with harvesting contractors. The impact of random variables is relatively minor on the wood fiber supply network, and it can be modeled using standard probability distributions (Haimes, 2004). However, extreme events are difficult to predict and may have serious consequences on the supply of wood fiber to mills, which makes them much harder to model in the supply chain management process. In addition, the demand of products by customers is also stochastic in nature. Demand uncertainty is caused due to prevailing volatilities in the business environment and ever changing markets, with constantly shifting and increasing customer expectations (Jung et al., 2004). Based on the timeframe over which demand uncertainties affect the supply chain system, these can be categorized into short-term or long-term demand uncertainties (Gupta & Maranas, 2003). Short-term demand uncertainties may include day-to-day variations, and canceled/rushed orders, whereas, long-term demand uncertainty refers to seasonal demand variations occurring over longer periods of time. Therefore, there is a trade-off between inventory holding costs and shortage costs for the entire supply chain.

The total annual demand of paper is 42 thousand tonnes in the domestic market, 240 thousand tonnes in the US market, and the annual demand of textiles in the Asian market is 72 thousand tonnes, with monthly random demand variations. The total annual supply of wood fiber from the forest management units is 1.65 million m³, with random monthly supply variations by the suppliers (data obtained in consultation with the pulp mill managers). Based on historical data, the demand of paper in the domestic and the US market, and the demand of textiles in the Asian market follow a Poisson distribution with a known monthly average of 3.5, 20, and 6 thousand tonnes, respectively. The random monthly supply of pulp logs from each of the small, medium and large suppliers also follows a Poisson distribution with a known monthly average of 24.7, 49.5, and 63.3 thousand m³, respectively. The cost parameters of the suppliers are shown in Table 1. The suppliers harvest trees from the forest management units and convert these into pulp log (54%), saw logs (18%), bush chips (13%), hardwood logs (15%), and hog fuel (13%). It is assumed that the sawmills are of different capacities, and the suppliers supply 10% of their harvested saw logs to sawmill 1, 15% to sawmill 2, 20% to sawmill 3, 25% to sawmill 4, and 30% to sawmill 5. The sawmills convert the saw logs to lumber (50%), saw chips (25%), offcuts (10%), shavings and saw dust (10%), and bark (5%). The hardwood mills convert the hardwood logs to veneer (50%), hardwood chips (25%), offcuts (10%), shavings and sawdust (10%), and bark (5%). The pulp recovery is assumed to be 50% from pulp logs,

Table 1. Cost parameters of the integrated supply chain model agents

	Suppliers (\$/m3)	Merchandizing yard (\$/m3)	Pulp mill (\$/m3)	Paper/textile mills (\$/m3)	Wholesalers (\$/tonne)	Retailers (\$/tonne)
Harvesting cost	7.00	-	-	-	-	-
Ordering cost	-	-	5.00	4.50	3.50	2.50
Holding cost	4.50	6.50	5.50	3.50	2.50	1.50
Shortage cost	4.75	6.75	5.75	3.75	2.75	1.75
Handling cost	6.00	8.00	7.00	5.00	4.00	3.00
Transportation cost	6.75	7.00	7.75	5.75	4.75	3.75

and 15% from bush and saw chips. In addition, 10% (of total pulp production) black liquor is also produced from the pulp mill. The production cost of pulp in the pulp mill is assumed to be \$600 per tonne, if the pulp mill is running at more than 20% of its full production capacity, and \$1,000 per tonne otherwise. This is because higher fixed costs at less than 20% running capacity increase the overall production cost. The pulp mill distributes its production to the paper and textile mills, with 11% of pulp production supplied to domestic paper mills, 67% to US paper mills, and rest 22% to Asian textile mills. The average sales price of pulp to the paper and textile mills is assumed to be \$1,140 per tonne. The paper and textile mills convert 75% of the pulp received into paper and textiles.

The simulation model starts by generating stochastic monthly demand of paper from the domestic and the US customers, and stochastic monthly demand of textile from the Asian customers. The supply chain agents of each product receive the monthly demand from the customers, and based on their inventory level either supply the desired quantity of product to the customers or place an order to the upstream agent. The length of the planning horizon for the simulation model is one year, and the simulation time period is one month based on our discussions with the pulp mill managers. The supply chain agents are built as autonomous units capable of making decisions and having clearly defined interfaces with other agents in the model.

4. Results and discussion

4.1. Effects of supply and demand uncertainty

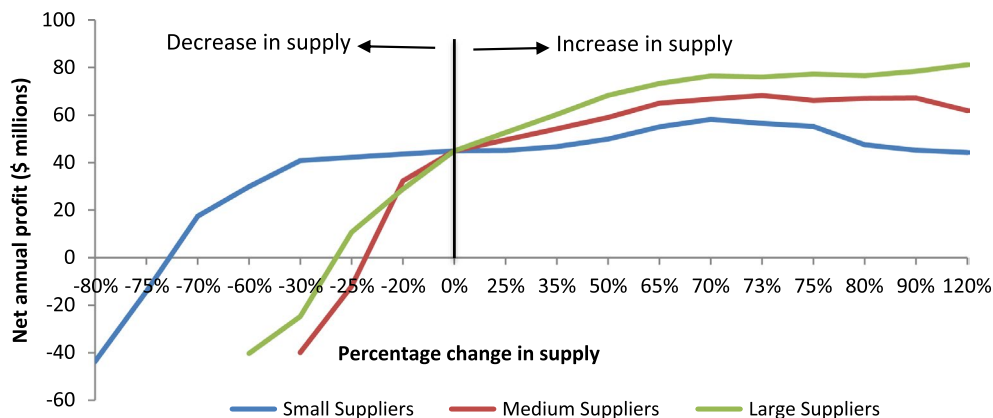
The performance of 1,000 simulations leading to the optimized solutions, obtained by maximizing the net annual profit of the pulp mill, is analyzed first without a merchandizing yard and then by including a merchandizing yard in the supply chain under supply and demand uncertainty (Table 2). Under supply and demand uncertainty without merchandizing yard scenario, the optimization model converges to a net annual loss of \$59.9 million to the pulp mill, with the pulp mill running capacity of only 10% and a customer satisfaction of 9% (i.e. only 9% of the customers' demand is satisfied). With a merchandizing yard in the supply chain, there is a net annual profit of \$26.7 million to the pulp mill, indicating a profit of 144.62% as compared to the BAU without merchandizing yard scenario. In addition, the pulp mill running capacity increases to 70%, and customer satisfaction to at least 50%. Therefore, the rest of the analysis was done by including a merchandizing yard in the model.

With decrease in supply by small, medium and large suppliers, the model does not generate a feasible solution for customer satisfaction more than 45%, and pulp mill running capacity of more than 60%. That means a decrease in supply by each supplier has an impact on production of pulp in the pulp mill, as well as on customer satisfaction levels. A decrease in supply by any of these suppliers also negatively impacts the net annual profit of the pulp mill (Figure 3). On the other hand, an increase in supply by any of the three types (small, medium, and large) of suppliers keeps the pulp

Table 2. Net annual profit and supply chain costs (\$ millions) with and without merchandizing yard (MY)

	BAU with MY	BAU without MY	Percentage age increase
Net profit of the pulp mill (\$)	-59.93	26.74	144.62
Annual pulp mill cost (\$)	65.04	219.09	236.85
Annual downstream supply chain cost (\$)	111.51	283.61	154.33
Annual upstream supply chain cost (\$)	149.67	287.99	92.42
Total annual supply chain cost (\$)	196.14	352.51	79.72

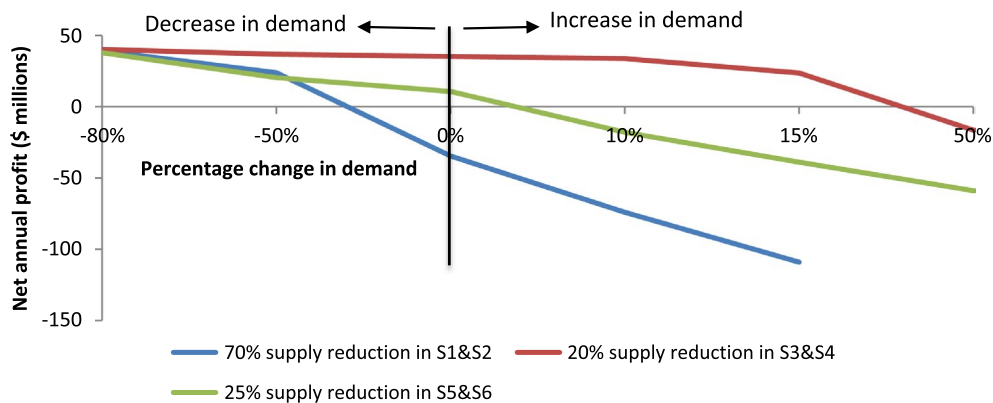
Figure 3. Effect of variation in supply by small, medium, and large suppliers on net annual profit.



mill running and the net annual profit of the pulp mill is always positive. We further analyzed the supply uncertainty scenarios to study the extent of supply reduction by each supplier that reduces the net annual profit of the pulp mill to zero. We found that the model shows a positive net annual profit till the small, medium and large suppliers reduce their supply by 73, 23 and 27%, respectively (Figure 3). With restriction in supply by small, medium and large suppliers, the pulp mill is not able to meet the existing demand of customers, resulting in an increase in shortage cost, and subsequent net annual loss to the pulp mill.

Next, the combined impact of uncertainty in supply and demand was analyzed. Different scenarios of changes in demand were carried out along with restriction in supply by small (73%), medium (23%), and large (27%) suppliers, as found in results above. The results of these experiments on net annual profit of the pulp mill are shown in Figure 4. With an increase in demand from customers and with restrictions in supply from suppliers, the pulp mill shows a net annual loss. We further analyzed the demand uncertainty scenarios to study the extent of demand increase with restricted supply that reduces the net annual profit of the pulp mill to zero. We found that the model shows a positive net annual profit as long as the increase in demand is 30% and 4% under restrictions in supply from medium and large suppliers, respectively (Figure 4). The pulp mill is unable to meet the increased market demand with a reduced supply from medium or large suppliers. This results in increased shortage cost and subsequently net annual loss to the pulp mill. Therefore, policies should be put in place to maintain a regular supply from the medium and large suppliers, as reduction in supply by these suppliers has an immediate impact on continuous operation of the pulp mill and its net annual profit.

Figure 4. Effect of variation in demand with reduction in supply by small (S1 & S2), medium (S3 & S4) and large suppliers (S5 & S6) on net annual profit.



4.2. Performance of merchandizing yard under uncertainty

The merchandizing yard helps in managing risks associated with supply and demand uncertainty by ensuring continuous operation of the pulp mill, resulting in a net annual profit, and an increased customer satisfaction. By including a merchandizing yard in the supply chain, the holding and shortage costs of downstream side supply chain agents are substantially reduced (Table 3), whereas their handling and transportation costs are high, as they are now handling larger volume of products (Table 3). The incorporation of the merchandizing yard also reduces the inventory parameters (s , S) of the entire downstream supply chain (Table 4). The total annual setup and operational cost of the merchandizing yard is \$55 million. About half of this cost is used for handling the material in the merchandizing yard and about one-fourth of this cost is the holding cost. The handling and holding costs of both the receiving and supply units of all supply chain agents are generally low, whereas the production and transportation costs are high, as large amounts of materials are flowing through the supply chain in the presence of a merchandizing yard (Table 5). Although, the establishment and operation of a merchandizing yard reduces the shortage cost in the supply chain, it increases the inventory handling, holding and transportation costs, as the merchandizing yard needs to procure and hold more inventory. The results of sensitivity analysis reveal that the merchandizing yard is economically viable and the pulp mill will make a net annual profit only if the sales price of pulp is at least \$680 per tonne.

The merchandizing yard further helps in substantially increasing (633%) the supply of pulp by the pulp mill. Because of the presence of merchandizing yard, the sawmills and hardwood mills are also able to run at a higher capacity, and supply higher amounts of forest products (lumber, saw chips, offcuts, shavings, and bark) to the markets. In the present scenario, we only consider one central merchandizing yard, which is located between the suppliers and the mill. However, in the real world, there could be multiple merchandizing yards depending on harvesting locations and road network. The size and location of the merchandizing yard were not analyzed in this study, being outside the scope of this paper. These results demonstrate the use of optimal production-inventory model to the specific case of the pulp mill in this paper. However, the integrated supply chain model can be used by for any forest products industry as it considers the entire supply chain structure and manages all business decisions both upstream and downstream in the supply chain.

Table 3. Supply chain costs of retailers and wholesalers (\$ millions) with and without merchandizing yard (MY)

	Domestic		US		Asian	
	Without MY	With MY	Without MY	With MY	Without MY	With MY
<i>Retailers</i>						
Holding cost (\$)	0.02	0.01	0.08	0.08	0.03	0.03
Shortage cost (\$)	0.41	0.23	2.34	1.36	0.70	0.38
Handling cost (\$)	0.04	0.09	0.24	0.54	0.08	0.18
Transportation cost (\$)	0.01	0.08	0.08	0.46	0.02	0.15
<i>Wholesalers</i>						
Holding cost (\$)	0.51	0.09	1.38	1.23	0.35	0.26
Shortage cost (\$)	1.33	0.55	5.07	3.28	1.14	0.57
Handling cost (\$)	0.82	0.23	2.27	2.43	0.59	0.56
Transportation cost (\$)	0.01	0.09	0.07	0.55	0.02	0.18

Table 4. Inventory policy parameters (s, S in thousands) of retailers, wholesalers, paper and textile mills (receiving unit, RU and supply unit, su), and pulp mill (receiving unit, RU and supply unit, SU) with and without merchandizing yard (MY)

	Domestic		US		Asian		Without MY	With MY
	Without MY	With MY	Without MY	With MY	Without MY	With MY		
<i>Retailers</i>								
s (re-order level) (tonne)	0.87	0.80	4.77	4.76	1.85	1.76		
S (re-order up to level) (tonne)	6.20	5.80	30.38	30.00	8.95	8.95		
<i>Wholesalers</i>								
s (re-order level) (tonne)	16.91	3.08	45.99	40.84	11.77	8.56		
S (re-order up to level) (tonne)	37.59	24.46	91.15	99.26	26.85	26.85		
<i>Paper and textile mills (RU)</i>							<i>Pulp mill (RU)</i>	
s (re-order level) (tonne)	27.14	14.87	208.33	55.37	15.85	17.73	61.18	182.84
S (re-order up to level) (tonne)	50.00	32.53	430.50	134.79	35.71	36.48	125.21	443.64
<i>Paper and textile mills (SU)</i>							<i>Pulp mill (SU)</i>	
s (re-order level) (tonne)	20.41	3.08	104.17	40.84	11.92	11.35	45.99	91.42
S (re-order up to level) (tonne)	37.59	24.46	215.25	100.76	26.85	26.85	94.13	203.81

Table 5. Supply chain costs (\$ millions) of pulp mill, domestic paper mills, US paper mills, and Asian textile mills with and without MY

	Pulp mill		Domestic paper mills		US paper mills		Asian textile mills	
	Without MY	With MY	Without MY	With MY	Without MY	With MY	Without MY	With MY
<i>Receiving units</i>								
Holding cost	17.23	12.09	1.14	0.62	2.57	2.33	0.66	0.74
Handling cost	22.95	22.43	1.65	1.02	3.77	4.09	0.98	1.32
Transportation cost	1.13	7.79	19.96	0.15	0.12	0.89	39.93	0.29
<i>Supply units</i>								
Holding cost	6.88	6.03	0.86	0.13	1.93	1.72	0.50	0.47
Handling cost	8.98	9.30	1.24	0.28	2.84	3.03	0.74	0.87
Production cost	21.94	140.80	0.02	0.15	0.13	0.93	0.04	0.31
Transportation cost	0.25	1.79	0.01	0.11	0.09	0.67	0.03	0.22

5. Conclusions

The Canadian forest products industry is operating under uncertain supply of wood fiber from the forest management units and uncertain demand of forest products from the customers. Under these stochastic supply and demand conditions, the forest industries are unable to operate at full capacity production, and are spending a substantial portion of their costs in managing their inventory. An optimal production-inventory model was developed for the forest products industry that manages all inventory planning decisions, both upstream and downstream in the supply chain, in the presence of continuously changing information across the entire supply chain. The integrated model is then used as a case study to see the impact of supply and demand uncertainty in a pulp mill

supply chain. Using the model, it is found that supply uncertainty caused by reduction in supply by wood fiber suppliers has a direct impact on production of the pulp mill and customer satisfaction. Therefore, policy measures need to be developed to ensure un-interrupted supply from suppliers to improve the competitiveness of forest industry in the global markets. When a merchandizing yard is included between the suppliers and the pulp mill, it absorbs supply and demand shocks and ensures continuous production of the pulp mill, as well as improves customer satisfaction, resulting in net annual profit to the pulp mill. Future research should focus on integrating this production-inventory model with forest products trade models (Buongiorno et al., 2003) and including product markets for secondary industries, such as biorefineries.

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Note

1. For a comprehensive review of the supply chain network of the Canadian forest products industry, please refer to our review paper (Shahi & Pulkki, 2013a).

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